Food and Agriculture Organization of the United Nations

Valuing, restoring and managing "presumed drylands"

Cerrado, Miombo–Mopane woodlands and the Qinghai–Tibetan Plateau

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Cover photograph: Rheas in Cerrado - Rhea walking around the reserve. The Cerrado shelters more than 1,600 species of mammals, birds and reptiles. ©FAO/Anne Branthomme

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Foreword

Notwithstanding some progress made towards the Sustainable Development Goals, poverty and food insecurity prevail, while the ecosystems that provide critical natural services continue to be threatened and degraded. In particular, land management decisions and land-use changes in the world's drylands have significant environmental implications that extend well beyond their boundaries. The world's drylands cover about 6.1 billion hectares and are characterized by moisture deficit conditions, with water loss from evaporation and transpiration by plants exceeding precipitation.

The cost of inaction in regard to land degradation has been assessed as being at least three times that of investing in restoration initiatives in Asia and Africa, thus making restoration and sustainable management – including of dryland forests – a sound investment. Over the past three decades, a long-overdue shift in the narrative has been taking place by increasingly emphasising human and social capital and responding to each dryland context independently, taking into account local players, institutions, knowledge and needs.

There has never been a more urgent time to accelerate management actions in protecting, restoring and promoting the sustainable management and use of different ecosystem services than today. Therefore, identifying areas where restoration and sustainable management practices can provide the largest benefits is crucial for enabling the world's progress towards attaining land degradation neutrality commitments.

Drylands have gained increasing attention in research, policy and practice in the last decades. FAO's Committee on Forestry at its twenty-second session in 2014 called for action and investments in dryland assessments, monitoring, sustainable management and restoration. In 2019, FAO launched *Trees, forests and land use in drylands: the first global assessment* to provide the baseline for future monitoring and investment for the sustainable management of drylands. Unfortunately, the areas with dryland characteristics and at greater risk of becoming drylands in the near future, i.e. so-called "presumed drylands", remain poorly researched and undervalued.

This new global assessment provides an overview of the state of "presumed drylands", their resources and challenges. It offers economic scenarios to help guide decision-makers and planners identify appropriate investment by comparing the costs and benefits of business-as-usual with land degradation neutrality scenarios in the Cerrado of South America, the Miombo–Mopane woodlands in southern and eastern Africa and the Qinghai–Tibetan Plateau. The methods include data collection through Collect Earth, a literature review, and an analysis of different initiatives and projects implemented in the presumed dryland areas. The findings were used to value the cost of halting land conversion and degradation in "presumed drylands" in response to land degradation neutrality commitments.

Post-pandemic recovery requires investments in ecosystem restoration and the implementation of targeted sustainable management practices and actions that maintain the ecosystem goods and services that humans rely on within the limits of our planet. Therefore, putting trees and forests back into degraded landscapes and applying other sustainable land management practices are important options, to not only increase ecological resilience and productivity, but also achieve the future we want – and need.

Acronyms and abbreviations

Plano ABC	Brazil's Low Carbon Agriculture Plan (agricultura de baixa emissão de carbono)
AFSP	Agroforestry Food Security Programme (initiated by the World Agroforestry Centre)
AI	aridity index (see P/PET)
ASM	Amazon soy moratorium
BAU	business-as-usual scenario
BNDES	National Bank for Economic and Social Development (pt. El Banco Nacional de Desarrollo)
BRL	Brazilian real
CA	conservation agriculture
CBD	UN Convention on Biological Diversity
CER credits	certified emission reduction credits
CFU	Conservation Farming Unit, Zambia
CSA	climate-smart agriculture
DRC	Democratic Republic of the Congo
EMBRAPA	Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária)
ET	evapotranspiration
EX-ACT	FAO's Ex-Ante Carbon-balance Tool
FMNR	farmer-managed natural regeneration
FOB price	free on board price
FRA	Global Forest Resource Assessment
GDP	gross domestic product
GEF	Global Environment Facility
GHG	greenhouse gases
ICLF system (ILPF)	integrated crop–livestock–forest system (integração lavoura–pecuária–floresta)
ICTPEM	International Centre for Tibetan Plateau Ecosystem Management
IPC	Integrated Food Security Phase Classification
LDN	land degradation neutrality
MESA	Monitoring for Environment and Security in Africa
NICFI	Norway's International Climate and Forest Initiative
NPP	net primary production
NTFP	non-timber forest product
MATOPIBA	Region that comprises the Cerrado biome in the states of Maranhão, Tocantins, Piauí and Bahia
P/PET	aridity index (ratio of average annual precipitation and potential evapotranspiration)
PES	payments for ecosystem services
PV	present value
QTP	Qinghai–Tibetan Plateau
REDD+	Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries.
SCC	social cost of carbon
SLM	sustainable land management
SOC	soil organic carbon
tCO2eq	carbon dioxide equivalence (expressed per tonne of CO2 equivalent)
UNCCD	United Nations Convention to Combat Desertification

UNEP	UN Environment Programme
USD	United States Dollar
VCS	Verified Carbon Standard
UNEP–WCMC	UN Environment Programme–World Conservation Monitoring Centre
WDPA	World Database on Protected Areas
WOCAT	World Overview of Conservation Approaches and Technologies
WWF	World Wildlife Fund

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Executive summary

The United Nations Convention to Combat Desertification (UNCCD) defines drylands as areas with an aridity index value lower than 0.65, i.e. with an annual precipitation that is less than about two-thirds of potential evapotranspiration (P/PET < 0.65). Desertification, in turn, refers to land degradation, resulting from inappropriate agriculture, deforestation or drought, in arid, semi-arid and dry sub-humid areas, excluding hyper-arid zones (P/PET < 0.05). In 2007, the United Nations Environmental Programme–World Conservation Monitoring Centre (UNEP–WCMC) mapped the world's drylands, dividing them into four zones based on their aridity index and defined additional areas that have dryland features with aridity indices greater than or equal to 0.65 as "presumed drylands". Accordingly, the Convention on Biological Diversity (CBD) in 2010 refined the dryland definition and introduced some areas with presumed dryland features, but P/PET ≥ 0.65.

The recent FAO global drylands assessment *Trees, forests and land use in drylands* (2019)[1] highlighted that the different zones of drylands combined cover an area of around 6.1 billion hectares, or 41 percent of the world's land if "presumed drylands" are not included. As such, "presumed drylands" cover an additional 1 075 million hectares and are defined as those areas that do not meet the criterion of low annual precipitation levels, but are characterised by dryland features.

The present paper on "presumed drylands" adds to the larger global drylands assessment (FAO, 2019), which did not include in its analysis those areas that had dryland features, but an aridity index greater than or equal to 0.65. The global drylands assessment was carried out through the visual interpretation of satellite images using a software tool called Collect Earth, which is part of the Open Foris tool set. The interpretation was undertaken in the second half of 2015 in regional workshops prepared by FAO in collaboration with partner institutions representing academia, non-governmental organizations and other entities in order to define the global dryland zones based on their aridity index, including the "presumed drylands" covered by this paper. The data collection consisted of a visual estimation of land cover elements (trees and shrubs) within sample plots and the identification of the main land use category. Land use was classified utilising both the four land use categories established by FAO (forest, other wooded land, other land and inland water bodies) and the six land use categories defined by the Intergovernmental Panel on Climate Change (IPCC) (forest, grassland, other land, cropland, settlements and wetlands).

Because "presumed drylands" are considerably less extensive than the other dryland categories, not all the analyses presented in the global drylands assessment can be performed here. Nevertheless, this report provides a global analysis of where "presumed drylands" are located, what the main land uses are and an initial overview with a more detailed analysis of the land use subtypes. Following the global overview, the report focuses on the areas where "presumed drylands" are most abundant, i.e. the Cerrado in South America, the Miombo–Mopane woodlands in southern Africa and the Qinghai–Tibetan Plateau in South Asia, Central Asia and East Asia.

For each study area, an in-depth literature review was undertaken in order to assess the status and challenges of "presumed drylands", and the different restoration and management practices and approaches being employed. Dryland experts and project managers were questioned about current practices, and provided additional information on projects and initiatives shaping the status of these areas. The assessment applied an innovative approach using satellite imagery, biophysical modelling and economic valuation methods, combined with documented evidence on the many benefits of sustainable land management. Economic scenarios for the Cerrado in South America and the Miombo–Mopane woodlands in southern Africa were developed to highlight the costs and benefits of business-as-usual or land degradation neutrality decision-making. For the Qinghai–Tibetan Plateau, available evidence was analysed to better understand the impacts of grazing management towards improving the livelihoods and resilience of local communities.

[1] http://www.fao.org/documents/card/en/c/ca7148en

THE MIOMBO WOODLANDS

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1. Introduction

1.1 LAND DEGRADATION – A SERIOUS AND COSTLY THREAT

Balancing the competing needs to meet social, economic and environmental goals is crucial for sustaining our planet. However, global phenomena such as population growth, economic development and climate change, and the pressures on the Earth's soils and vegetation are increasing dramatically (Montanarella, 2016). The rapid expansion of agricultural land subject to unsustainable, intensive farming approaches leads to such negative effects as soil erosion, organic carbon depletion, nutrient losses and salinization (Smith *et al.*, 2016). According to the United Nations Convention to Combat Desertification (UNCCD), the temporary or permanent decline in land resources such as soils and vegetation is due to direct and/or indirect human activities, entailing a reduction or loss of the ecological and/or economic productivity of the land. Consequently, the world is not on track to achieve zero hunger by 2030 (FAO *et al.*, 2020).

Land management decisions and land use changes in the world's drylands have significant environmental and social implications that extend well beyond their boundaries. It is estimated that around one third of the global land area is already affected by land degradation to some degree, to which 33 percent are moderately to highly degraded (FAO, 2021). Certain findings suggest concomitant losses in the global value of ecosystem services of around USD 6.3 trillion each year, or almost three times the entire economic value of the agricultural sector (Sutton *et al.*, 2016). With regards to climate change adaptation and mitigation, land degradation also reduces the potentially sizeable capacity of soils – the second largest pool of carbon after oceans – to offset anthropogenic greenhouse gas emissions (Sanderman, Hengl and Fiske, 2017; Minasny *et al.*, 2017).

1.2 WHY ASSESS THE RESOURCES IN DRYLANDS AND "PRESUMED DRYLANDS"?

In 2007, the United Nations Environment Programme–World Conservation Monitoring Centre (UNEP–WCMC), in its global delineation of dryland areas, defined drylands as all land areas with an aridity index (AI)[2] of less than 0.65. Drylands are further subdivided into hyper-arid (AI < 0.05), arid (AI ≥ 0.05 and < 0.20), semi-arid (AI ≥ 0.20 and < 0.50) and dry sub-humid (AI ≥ 0.50 and < 0.65). The term "presumed drylands" is used in this report to refer to those areas identified by UNEP-WCMC as "presumed included" in the CBD definition of drylands (UNEP-WCMC, 2007). These are areas with an AI equal to or above 0.65 but having dryland features, based on annual precipitation, duration of dry season, occurrence of fires, or vegetation types. Covering about 41 percent of the Earth's land surface, dryland areas are much larger if "presumed drylands" are included. This assessment confirmed that 48 percent of the Earth's land surface is covered by dryland when "presumed dryland" areas are included.

In 2015–2017, FAO worked with more than 200 experts, with knowledge of the land and land uses in specific dryland regions, in order to analyse the interpretation of images using a software tool called Collect Earth. This broad collaboration resulted in a full report on *Trees, forests and land use in drylands: the first global assessment 2019* (FAO, 2019). The assessment adopted the dryland definition and the map of the global drylands provided by UNEP–WCMC (2007). The maps showed that "presumed drylands" cover 1 075 million hectares of land and are unevenly distributed globally, located in Africa (36 percent), South America (24 percent) and Asia (27 percent). Furthermore, our assessment showed that "presumed drylands" include 322 million hectares of forest, of which more than half has a closed tree canopy with a tree cover of more than 70 percent. The largest homogeneous area of "presumed drylands" in South America is found in Brazil with approximately 174 million hectares. In Africa, the greatest contiguous area is represented by the Miombo–Mopane woodlands and covers approximately 266 million hectares. The third largest contiguous area of "presumed drylands" is found in China and covers approximately 153 million hectares (see Figure 16 in Chapter 3 for the location of the three largest areas on the "presumed drylands" globally).

[2] Aridity index: the ratio of annual precipitation and mean annual potential evapotranspiration

Box 1
Distinguishing drylands from "presumed drylands"

The United Nations (UNEP, 1992; EMG, 2011) defines drylands as lands where the ratio of annual precipitation and mean annual potential evapotranspiration, also known as the aridity index (AI), is no more than 0.65.

Based on this definition, UNEP–WCMC (2007) has mapped the world's drylands, dividing them into four zones (Figure 1) based on their aridity index:

- Hyper-arid: AI less than 0.05
- Arid: AI greater than 0.05, but less than 0.2
- Semi-arid: AI greater than 0.2, but less than 0.5
- Dry sub-humid: AI greater than 0.5, but less than 0.65

The dry sub-humid zone – the least dry of the four zones – accounts for 22 percent of the total dryland area. Major components of this zone are the Sudanian savanna, forests and grasslands in South America, the tree steppes of eastern Europe and southern Siberia, and the Canadian prairie. Most dryland forests occur in this zone, as do some large, irrigated, intensively farmed areas along perennial rivers.

At the other extreme, the hyper-arid zone is the driest zone; it constitutes 16 percent of the total dryland area. This zone is dominated by deserts; the Sahara alone accounts for 45 percent of the hyper-arid zone, and the Arabian Desert constitutes another large component.

The semi-arid and arid zones comprise 37 and 25 percent, respectively, of the total dryland area.

UNEP–WCMC (2007) also defined areas of so-called "presumed drylands", i.e. areas with an AI above 0.65, but having dryland characteristics. Delineation of these areas has been based on the absence or presence of dryland features, such as precipitation, duration of dry season, occurrence of fires, or vegetation types.

"Presumed dryland" zones – covering 1 075 million hectares – are distributed among all the continents. The largest homogeneous areas are found in Africa, South America and Asia, constituting 87 percent of the total presumed area. Grasslands, barren land and cropland account for 60 percent of the total "presumed dryland" area, mostly in Asia. Forests cover around 30 percent, mostly divided between Africa and South America.

Source: UNEP. 1992. World Atlas of Desertification, United Nations Environment Programme; EMG (Environment Management Group). 2011. Global drylands: a UN system-wide response. Geneva, Switzerland; UNEP–WCMC. 2007. A spatial analysis approach to the global delineation of dryland areas of relevance to the CBD Programme of Work on Dry and Subhumid Lands. Cambridge, UK

The most important climatic characteristics of "presumed drylands" are scarce, often seasonal, precipitation, high temperatures and abundant solar radiation resulting in high evapotranspiration (Xu, Gong and Li, 2008; Reynolds *et al.*, 2007; Hunke *et al.*, 2015). Furthermore, their soils often have low fertility, are weathered and may lack adequate soil cover, making them susceptible to erosion (Msangi, 2007; Bustamante *et al.*, 2012; Chang *et al.*, 2014; Li, J.H. *et al.*, 2014; Hunke *et al.*, 2015). Aridity alone, for instance, is thought to affect around 14 million square kilometres or 40 percent of all arable land. While China and Brazil, which host most of the world's "presumed drylands", are among the seven countries with the highest absolute value of degraded arable land – semi-arid and arid countries in sub-Saharan Africa show the highest percentage shares of degraded arable land (Prăvălie *et al.*, 2021). Research initiatives and different projects which were reviewed during the course of this assessment revealed serious land degradation concerns and the scale and nature of the obstacles that need to be overcome in order to reverse these trends. While to date, little overall is known about these lands, their status and current practices, the analysis presented in this report revealed that agroforestry, plant residue retention and limiting tillage, natural regeneration and integrated landscape management are some of the most important approaches for improving the land's health and productivity.

While a call has been made for efforts to keep warming below 1.5 °C by the end of the century, the

impacts of 1.5 °C warming will have dire consequences on different ecosystems, mainly impacting dryland communities, their food security and access to productive resources (IPCC, 2019). Climate change-related risks to natural and human systems will rise with further temperature increases, resulting in changes in biodiversity, ecosystem composition, structure and functions. Furthermore, the degradation of current carbon stocks will affect progress towards achieving land degradation neutrality (LDN), which is vital for maintaining and enhancing healthy productive land for the benefit of current and future generations. In response to these worrying trends and processes, "presumed drylands" are a priority for activities to achieve LDN.

The approach applied in this report is aimed at helping decision-makers prioritize restoration and sustainable management interventions in "presumed drylands" that lead to more resilient landscapes. It links the spatial assessment on the extent and status of dryland forests, rangelands and agrosilvopastoral systems to the documented evidence on sustainable land and forest management practices in order to illustrate the investment perspectives of business-as-usual (BAU) and LDN scenarios. The assessment aims to fill a significant knowledge gap on these additional drylands called "presumed drylands" and provides an overview of potential restoration and sustainable management activities that would help achieve LDN in response to the UN Decade on Ecosystem Restoration (2021–2030).

1.3 METHODOLOGY

The global dryland assessment (FAO, 2019) was carried out through the visual interpretation of satellite images using a software tool called Collect Earth, which is part of the Open Foris tool set developed by FAO. Built on Google desktop and cloud computing technologies, Collect Earth facilitates access to multiple freely available archives of satellite imagery, including those with very high spatial resolution imagery available through Google Earth and Bing Maps, and those with high temporal resolution imagery available at Google Earth Engine (GEE). Collect Earth draws upon these archives and the synergy of imagery at multiple resolutions to enable an innovative method for land monitoring, referred to as augmented visual interpretation. The global assessment was carried out in the second half of 2015 in regional workshops prepared by FAO in a consortium with partner institutions representing academia, non-governmental organizations and other entities (Box 2).

Data collection consisted of a visual estimation of land cover elements (trees and shrubs) within sample plots and the identification of the main land use category. Each sample plot measured 70 × 70 metres (approximately 0.5 hectares), a size corresponding to the smallest patch that qualifies as forest according to the forest definition used in the Global Forest Resources Assessment 2020

Box 2
Some variables for which data were collected

- Plot identification: number, location, operator and time when saved
- Land use: FRA and IPCC category and accuracy, subcategory and accuracy, initial land use and year of change
- Remote sensing data source: satellite, date
- Site characteristics: dryland region, dryland category, FAO ecozone, biome, ecoregion, country, climate zone farming method, soil type, elevation, slope, aspect, calculated elevation range, calculated aspect, calculated slope
- Type and cover of:
  - ▷ vegetation elements: trees, shrubs, palms, bamboo, crops
  - ▷ infrastructure elements: houses, other buildings, paved roads, unpaved roads
  - ▷ water bodies: lakes, rivers
  - ▷ other elements: rock, bare soil, other
- Desertification trend
- Disturbances: impact type and grade; continual or year; accuracy
- Trees and shrubs: many or count
- Length of linear features: vegetation, paved roads, unpaved roads, paths.

(FAO, 2020b). The land use was classified using both the four land use categories of the Global Forest Resources Assessment (forest, other wooded land, other land and inland water bodies) (FAO, 2015b) and the six land use categories defined by the IPCC (forest, grassland, other land, cropland, settlements and wetlands) (IPCC, 2006). For more detailed information on the data collection and sampling methods, the global assessment can be referred to (FAO, 2019) (see Annex 2).

The present assessment was conducted selecting only the presumed dryland plots within the global dryland assessment database. Saiku Analytics, a free open-source software, was then used to visualize and aggregate data with a simple drag and drop interface. Microsoft Excel was used for further detailed analysis. Note that throughout the report, percentages may not add up to 100 due to rounding.

For the in-depth analysis of the three study areas *(*see Chapter 3), the same methodology was used as in Chapter 2 of the report of the global analysis (FAO, 2019). All the protected areas were downloaded from the World Database on Protected Areas (WDPA). Additional data were gathered for each of the study areas through a comprehensive literature review, using combinations of key words for each of the study areas (Cerrado, Miombo–Mopane, Qinghai–Tibetan Plateau), the countries in these areas (Brazil, Angola, the Democratic Republic of the Congo, Malawi, Mozambique, the United Republic of Tanzania, Zimbabwe, Zambia and China) and thematic words, i.e. dryland*, livelihood*, drought*, fire*, degradation, biodiversity, 'ecosystem service*', agroforest*, silv*, pastoral*). The literature included scientific peer-reviewed articles and grey literature (reports and other documents), obtained through the search engines Web of Science Core Collection, Google Scholar and Google.

The assessment also benefited from consultation with national experts in the countries of interest. Consultation meetings were organised in which the draft report was discussed. Moreover, the experts were asked to provide additional information on different projects and initiatives within presumed dryland areas in their countries that have been conducted to halt ecosystem degradation, restore degraded ecosystems, ensure food security and improve livelihoods, as well as on the best practices derived.

A cost–benefit analysis was performed over the 2020–2050 timeframe, for two of the study areas, the Cerrado and the Miombo–Mopane woodlands, comparing the net benefits of investing in the sustainable management of land, relative to continued degradation in the business-as-usual scenario.

While drylands have gained increasing attention in research, policy and practice in the last decades, "presumed drylands" remain poorly researched and undervalued. The following chapters aim at contributing to fill the information gap on "presumed drylands" and providing crucial information on their status, threats and challenges, as well as on potential investment opportunities to sustainably manage and restore these areas.

2. State of global "presumed drylands"

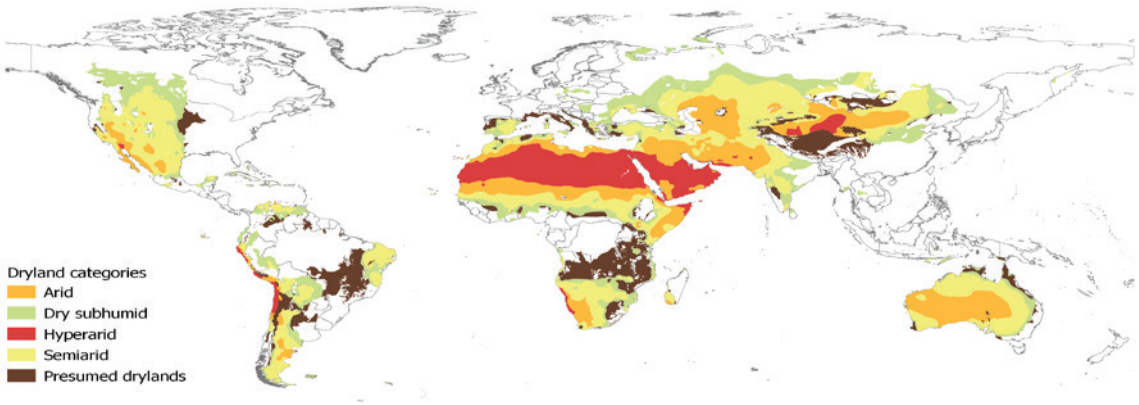
KEY FINDINGS

- Different zones of drylands combined cover an area of around 6.1 billion hectares, or 41 percent of the global terrestrial area.
- "Presumed drylands" cover 1 075 million hectares of the land's surface and they contain 322 million hectares of forest.
- Forest accounts for 30 percent of "presumed dryland" area, while other land accounts for 60 percent, other wooded land 8 percent and inland water bodies 2 percent. More than half of the presumed dryland forest area has a closed tree canopy with a cover of more than 70 percent.
- Many trees in "presumed drylands" grow outside the forest; 57 percent of grassland and 34 percent of cropland have at least some tree cover.
- When forest, other wooded land and trees outside forest are all considered, trees are present in half of the "presumed drylands" included in this assessment.
- "Presumed drylands" are distributed among all the continents, but most are found in Africa, South America and Asia.
- The largest homogeneous area of "presumed drylands" in South America is found in Brazil and partly in Argentina. The "presumed drylands" of Brazil alone, concentrated mostly in the Cerrado Ecoregion, comprise approximately 174 million hectares.
- "Presumed drylands" in Africa are mostly concentrated in the central and southern countries. A homogeneous area is represented by the Miombo–Mopane ecoregion, extending from the west coast in Angola to the east coast in Mozambique and the United Republic of Tanzania. Most of these areas are close to dry semi-humid areas and some semi-arid areas. "Presumed drylands" in Angola, Zimbabwe, Zambia, the Democratic Republic of the Congo (DRC), Mozambique, Malawi, the United Republic of Tanzania and Burundi cover approximately 266 million hectares.
- In Asia, the largest homogeneous presumed dryland area is found in China and covers approximately 153 million hectares. Some of these presumed dryland areas in China are also close to hyper-arid areas.

2.1 DISTRIBUTION OF "PRESUMED DRYLANDS", BIOMES AND FAO ECOZONES

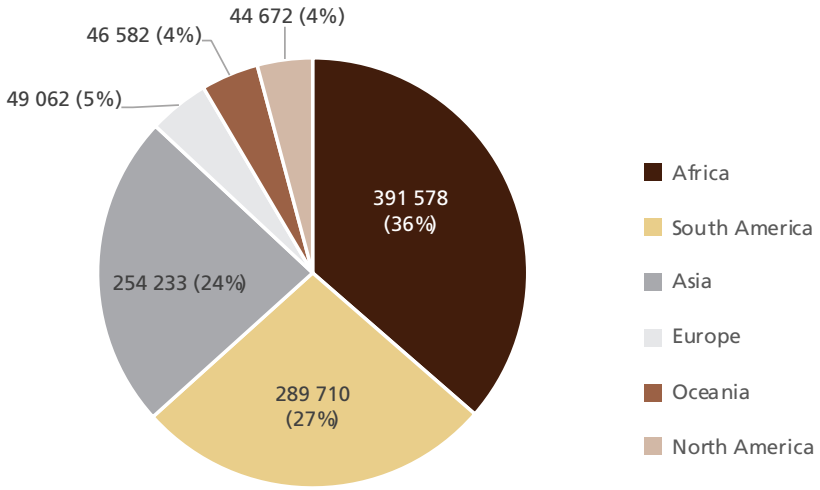
"Presumed drylands" cover 1 075 million hectares of the land's surface and are unevenly distributed globally, with most of them in Africa (36 percent), Asia (27 percent) and South America (24 percent) (Figure 1 and Figure 2).

FIGURE 1. Distribution of dryland and "presumed drylands"



Source: UN Map, 2018; UNEP-WCMC, 2007

FIGURE 2. Distribution of "presumed drylands" ('000 ha) by continent



Within the category of "presumed drylands", the most represented biomes are tropical and subtropical grasslands: savannas and shrublands accounting for 58 percent and montane grasslands and shrublands for 21 percent (Figure 3). Most of the tropical and subtropical grassland biomes are found in Africa (360 million hectares) and South America (221 million hectares), while most of the montane grassland and shrubland biomes are in Asia (174 million hectares) (Figure 4).

The most represented FAO ecozone (FAO, 2012b) is tropical with 62 percent of the area of "presumed drylands", while temperate regions cover 21 percent, subtropical 16 percent and boreal 1 percent (Figure 5). In Africa and South America, the most predominant ecozone is tropical, with 362 million hectares and 260 million hectares, respectively; the subtropical ecozone has a lower percentage. In Asia, the predominant ecozone is temperate and covers 183 million hectares, with a lower percentage of subtropical covering 56 million hectares (Figure 6).

2.2 DISTRIBUTION OF FORESTS AND OTHER LAND USES

Of the world's 1 075 million hectares of "presumed drylands", this assessment (Figure 7) classifies 30 percent as forest and 8 percent as other wooded land, while 60 percent is classified as other land, comprising predominantly grassland (27 percent), croplands (15 percent) and barren land, such as bare soil and rock (16 percent).

By continent, other land accounts for 88 percent of "presumed drylands" in Asia, 48 percent in Africa, 23 percent in Oceania, 56 percent in South America, 83 percent North America and 49 percent in Europe (Table 1).

Other wooded land is mostly found in Africa and Europe (Table 1).

The world's "presumed drylands" contain approximately 322 million hectares of forest, with 249 million of hectares divided between Africa and South America, with Africa having almost 1.5 times more than South America (Table 1).

When trees outside forest are also taken into consideration, trees are present in half (49.48 percent) of the "presumed drylands" (calculated from forests, other wooded land and other land with more than 2 percent of tree cover).

FIGURE 3. Distribution of biomes in "presumed drylands" ('000 ha)

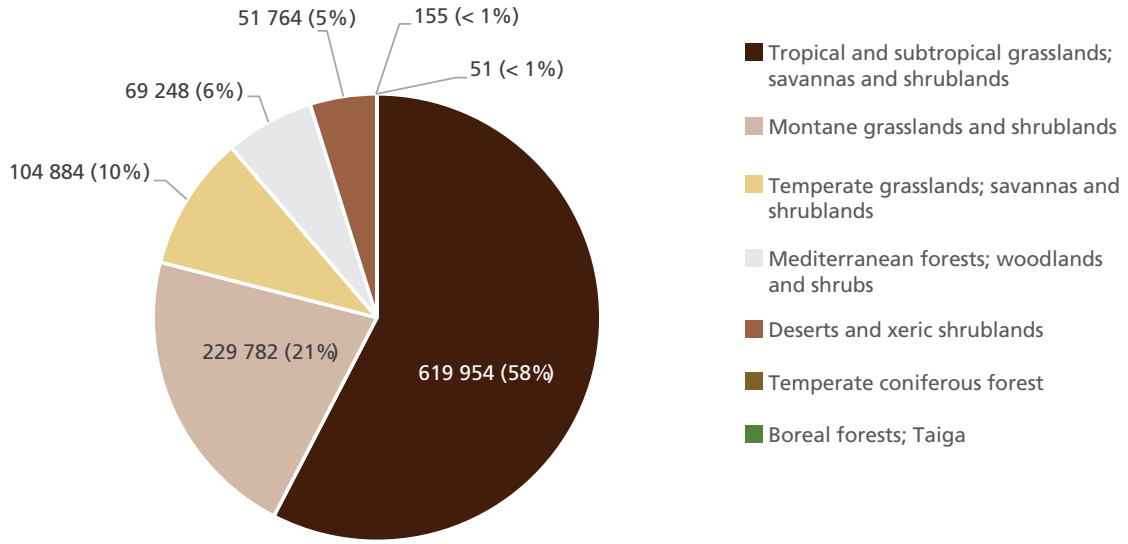


FIGURE 4. Distribution of biomes in "presumed drylands" ('000 ha) by continent

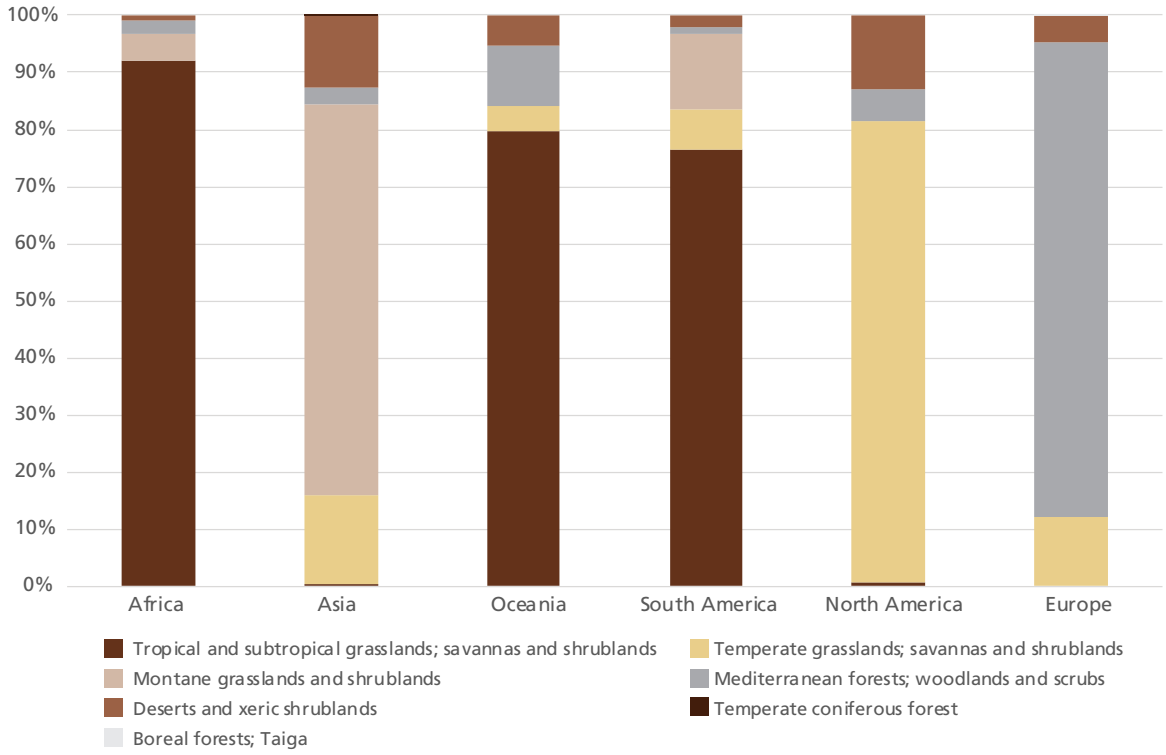


FIGURE 5. Distribution of FAO ecozones in "presumed drylands" ('000 ha)

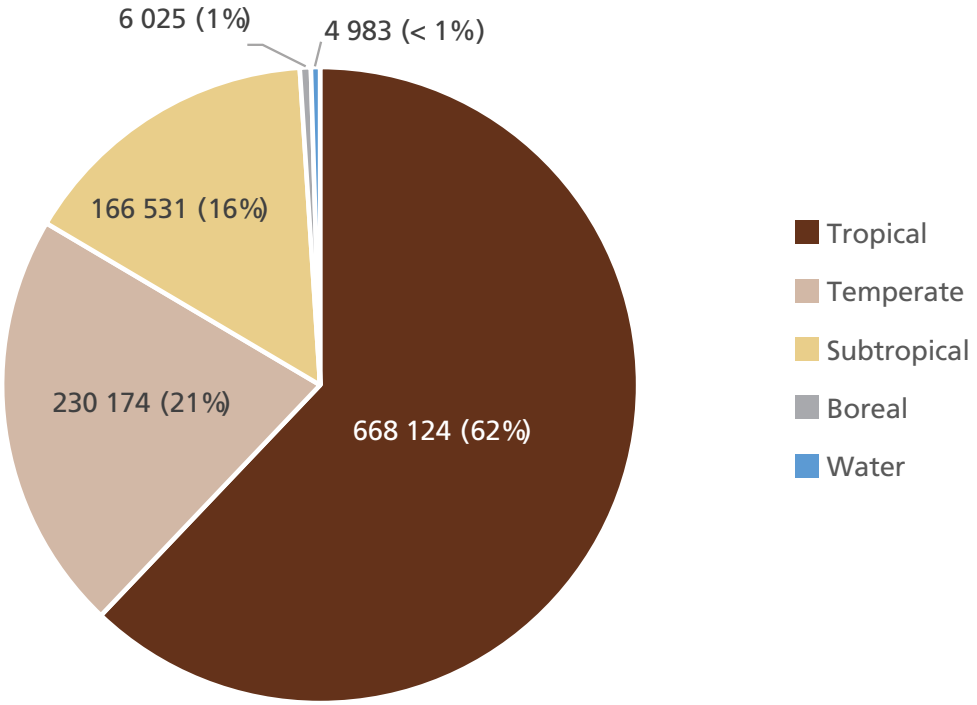


FIGURE 6 Distribution of FAO ecozones in "presumed drylands" ('000 ha) by continent

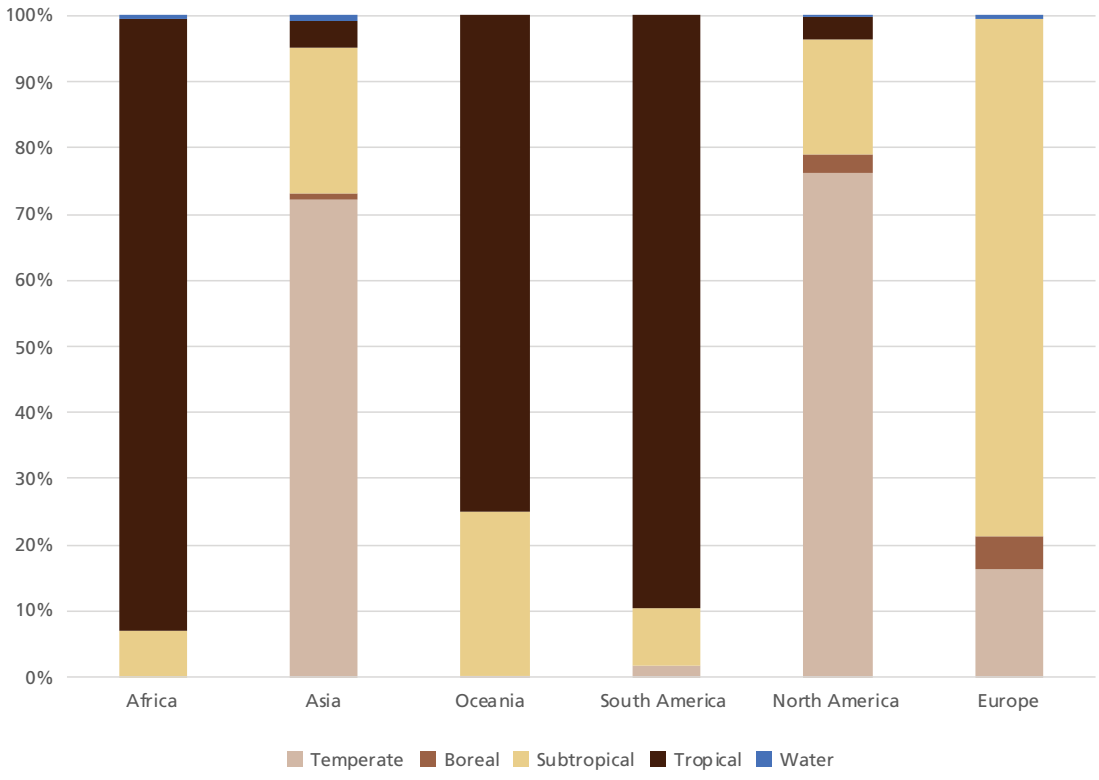


FIGURE 7. Distribution of land uses in "presumed drylands" ('000 ha)

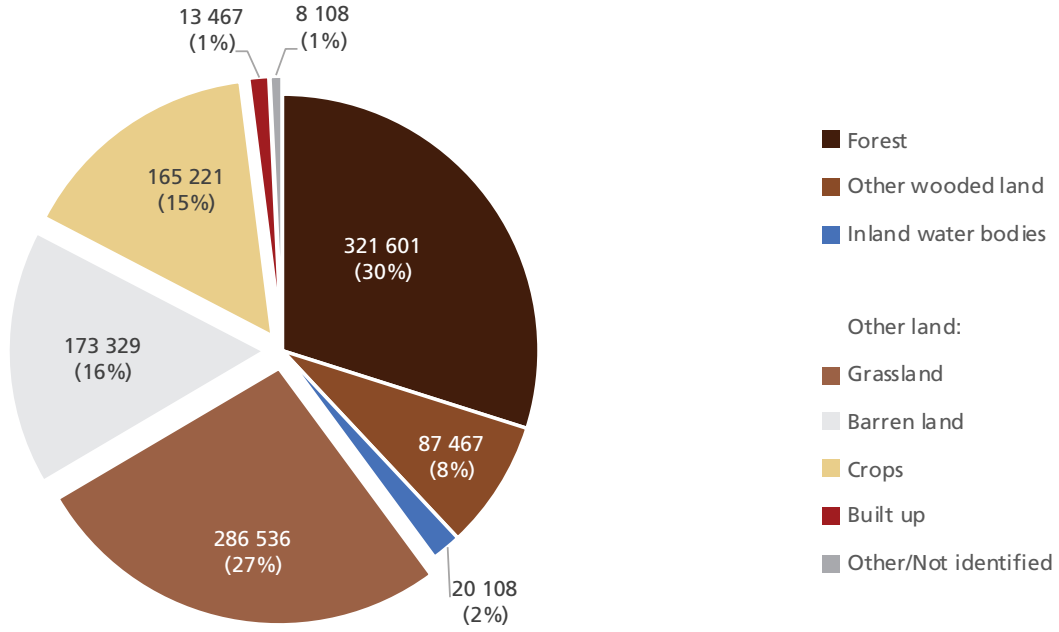


TABLE 1:
Distribution of land uses in "presumed drylands" by continent

Continent	Land use									
	Forest		Other wooded land		Other land		Inland water bodies		Total	
	'000 ha	percent	'000 ha	percent	'000 ha	percent	'000 ha	percent	'000 ha	percent
Africa	146 790	37	50 278	13	189 619	48	4 890	1	391 578	36
Asia	17 183	7	4 954	2	223 015	88	9 082	4	254 233	24
Oceania	31 293	67	2 904	6	10 560	23	1 825	4	46 582	4
South America	101 782	35	22 568	8	162 249	56	3 112	1	289 710	27
North America	5 504	12	1 562	3	37 146	83	461	1	44 672	4
Europe	19 049	39	5 202	11	24 072	49	740	2	49 062	5

2.3 VEGETATION IN FORESTS AND OTHER WOODED LAND

Presumed dryland forests are predominantly natural broadleaved forests (63 percent), while about 7 and 13 percent are natural coniferous – and mixed broadleaved and coniferous forests, respectively. The assessment did not identify the vegetation cover type for 10 percent of total forest. Broadleaved forests are most dominant in South America (88 percent), Oceania (61 percent), North America (57 percent) and Africa (55 percent).

The vegetation cover in other wooded land is mainly dominated by shrubland (54 percent of the total). The percentage of shrubland is highest in Asia (80 percent) and Africa (61 percent), but it is less than 40 percent in Oceania and Europe.

2.4 TREE CANOPY COVER

The assessment shows that 55 percent of presumed dryland forest has a dense canopy cover of 70–100 percent, and less than 1 percent of the forest has a canopy cover in the lowest range of 1 to 9 percent, which could be linked to forest management practices, temporarily unstocked forest or burned areas (Figure 8). On average, the tree canopy of presumed dryland forest is 66 percent (Table 2).

TABLE 2:
Average tree canopy (percent) of presumed dryland forest

Land use	percent
Forest	66
Other wooded land	9
Other land	3
Inland water bodies	1
All lands	22

Other wooded land exhibits the opposite pattern: less than half (40 percent or 35 million hectares) has no tree cover, consisting solely of bushes and shrubs, while 36 percent of other wooded land has a canopy cover of 1 to 9 percent (Figure 8).

The density of tree cover differs by continent. Of all the continents, canopy cover on average is highest in Africa and South America (Figure 9).

FIGURE 8. Tree canopy cover in Forest and Other wooded land

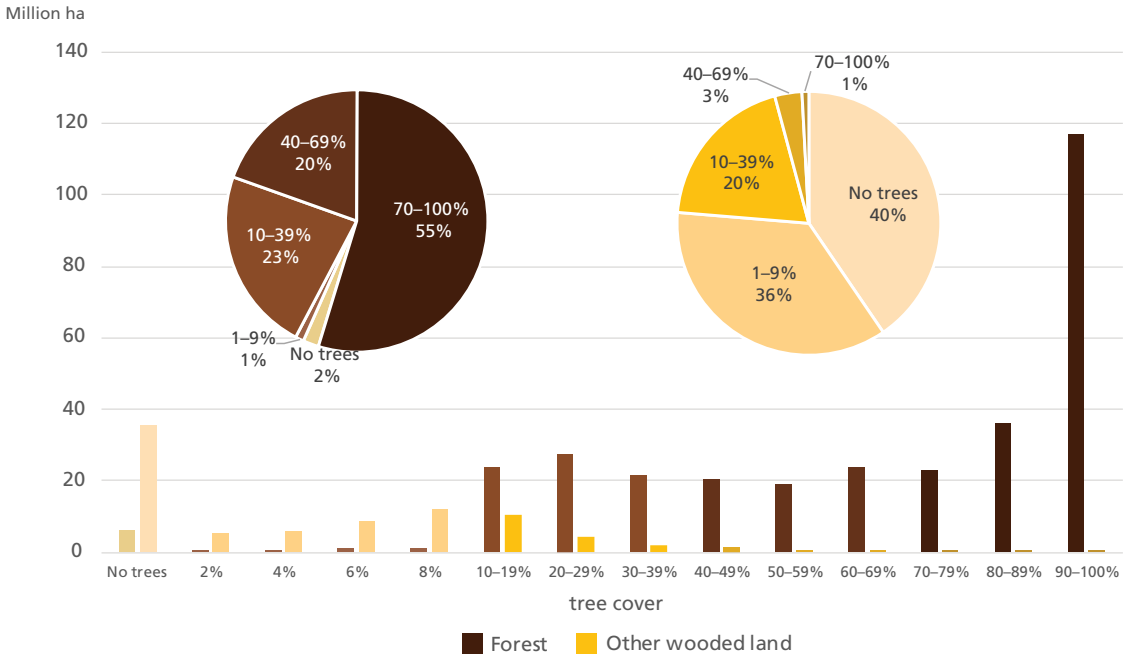
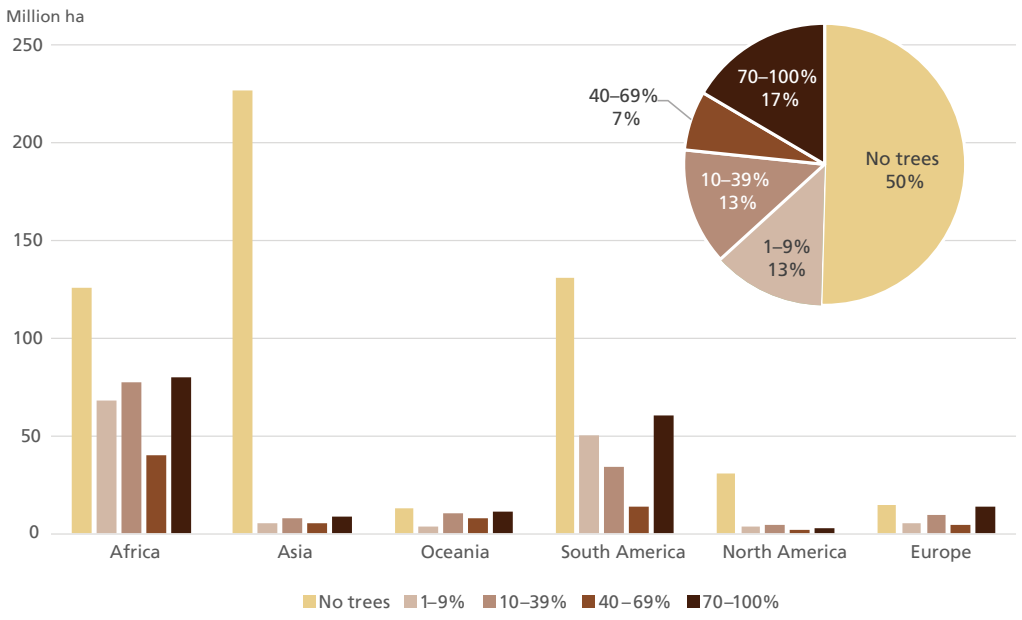


FIGURE 9. Tree canopy cover in "presumed dryland" by continent



2.5 SHRUB COVER

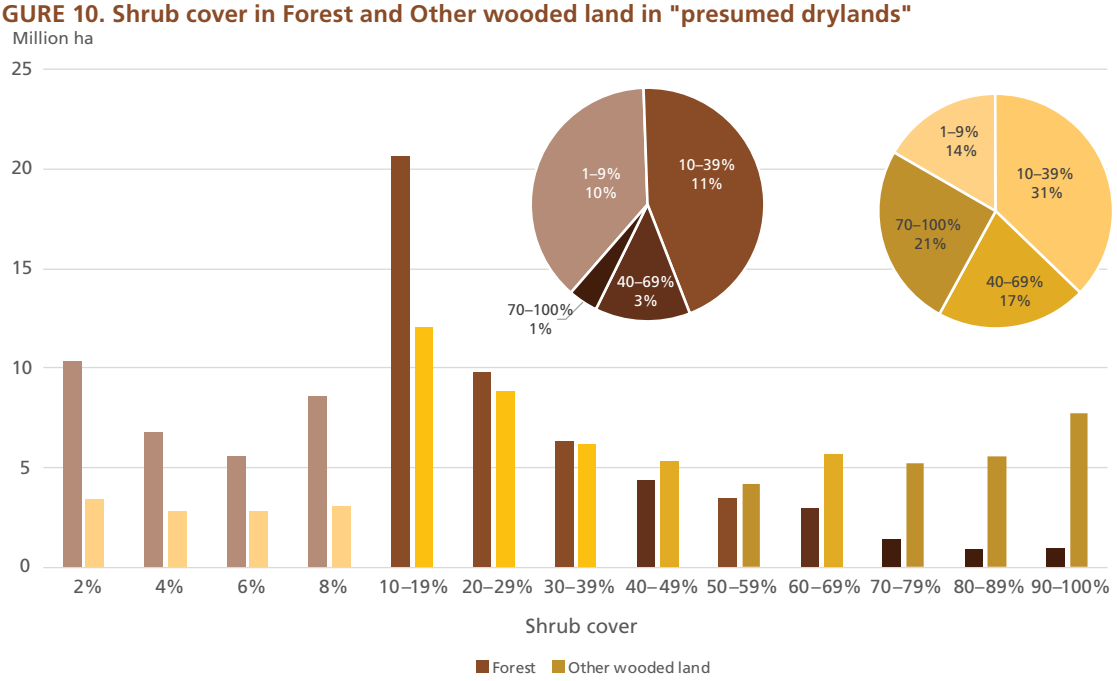
Overall, the average shrub cover in other wooded land in "presumed drylands" is approximately 36 percent, while in the forest it is about 6 percent (Table 3). However, in the forest, where the shrubs represent a vegetation sublayer, they are not always easy to detect, especially when the canopy is dense.

Mostly, the shrubs are evenly distributed in other wooded land in "presumed drylands". About 21 percent of other wooded land has a dense and continuous shrub cover (ranging from 70 to 100 percent), while less than 31 percent has a shrub cover ranging from 10 to 39 percent (Figure 10).

TABLE 3:
Average shrub cover (percent) in "presumed drylands"

Land use	percent
Forest	6
Other wooded land	36
Other land	17
Inland water bodies	4
All lands	6

FIGURE 10. Shrub cover in Forest and Other wooded land in "presumed drylands"



Africa and South America have the highest shrub cover by continent in other wooded land in "presumed drylands" (Figure 11).

Globally, only 11 percent of forest in "presumed drylands" has a shrub cover between 10 and 39 percent, while only 9 percent has a shrub cover of more than 40 percent.

2.6 OTHER LAND

Other land comprises 27 percent grassland (287 million hectares), 16 percent barren land (173 million hectares), 15 percent cropland (165 million hectares), and around 1 percent built-up and other or not identified, respectively (Figure 7). Globally, when grassland is added, likely used for pastoralism, cattle ranching and/or cropland, 42 percent of the "presumed drylands" could be used as agropastoral land. While the global report (FAO, 2019) found that other lands in Africa are mostly barren land, for the "presumed drylands" in Africa, other land is mostly covered by grassland and cropland (57 percent and 34 percent respectively) and the percentage of barren land is only 5 percent (Figure 12).

FIGURE 11. Shrub cover by continent for "presumed drylands"

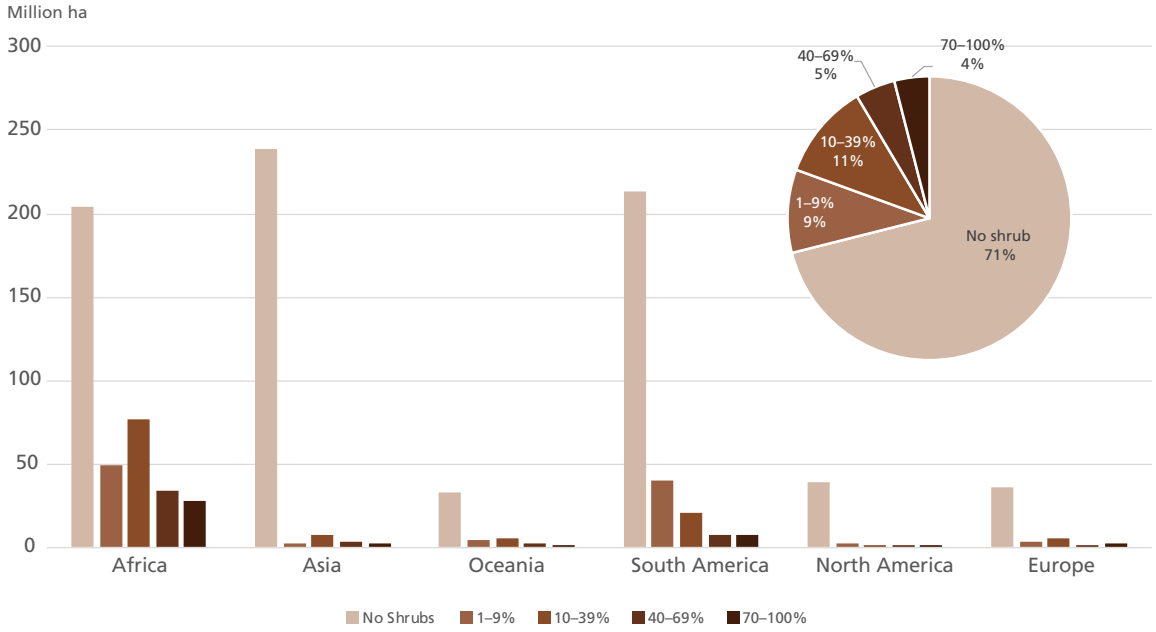


TABLE 4:
Land-use types in other land in "presumed drylands"

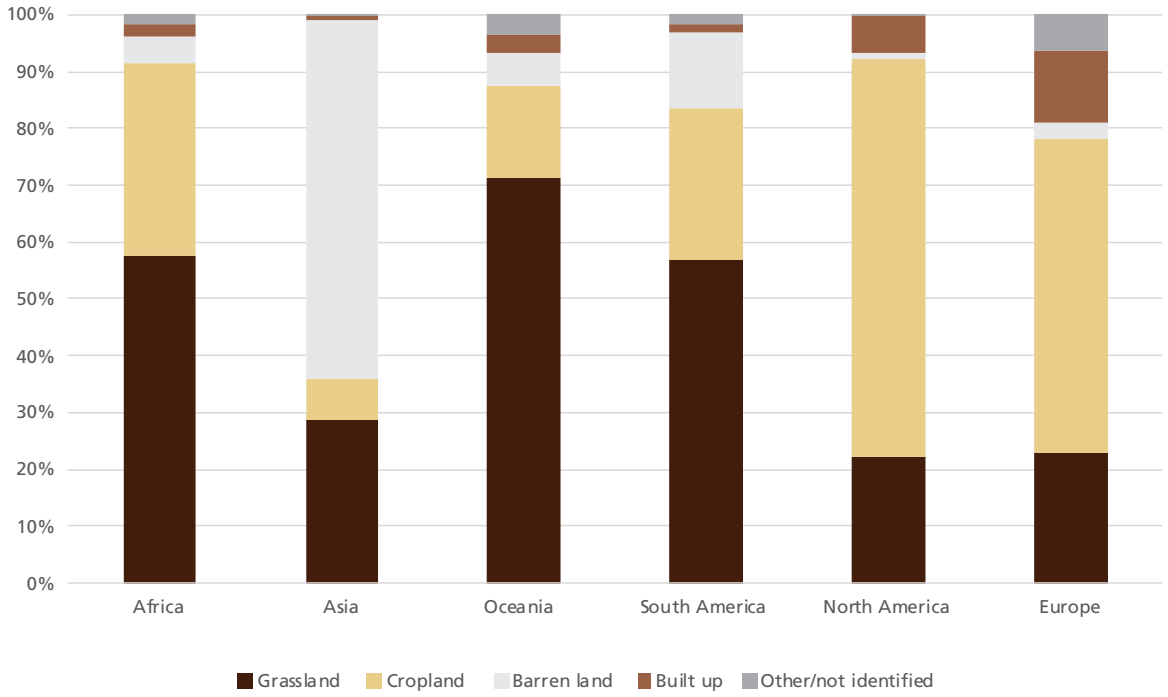
Land use	Land-use type	,000 ha	percent
Grassland		286 536	100
Cropland		165 221	100
	Irrigated crops	35 112	21
	Non-irrigated cropland	124 955	76
	Perennial crops (palms, orchards, others)	5 154	3
Barren land		173 329	100
	Rock or stone	119 348	69
	Sand and dunes	34 695	20
	Snow and glaciers	12 531	7
	Unknown	6 755	4
Built up		13 467	100
	Villages and urban settlement	7 432	55
	Infrastructure	5 805	43
	Mining	231	2
Other/not identified		8 108	100

Non-irrigated cropland represents 76 percent of total cropland in "presumed drylands" (Table 4), while only 21 percent comprises irrigated crops and 3 percent perennial crops (such as palms, orchards and others).

Cropland makes up 34 percent of other land in Africa and 27 percent in South America (Figure 12). Of all the continents (Figure 12), Asia has the highest percentage of barren land (63 percent), followed by South America (13 percent). Globally, of the barren land in "presumed drylands", 69 percent is represented by rock and stones, while 20 percent is covered by sand and dunes (Table 4).

In "presumed drylands", built-up land comprises 55 percent of villages and urban settlements, distributed mainly in North America and Europe, infrastructure 43 percent, and mining activity 2 percent, mostly in Africa (Table 4; Figure 12).

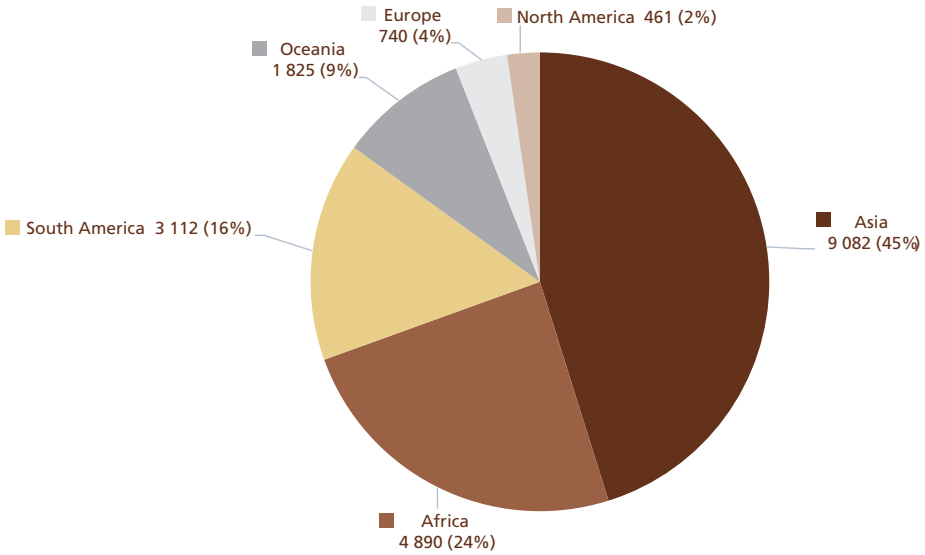
FIGURE 12. Land use in other land by continent in "presumed drylands"



2.7 INLAND WATER BODIES

Although inland water bodies only represent 2 percent of the presumed dryland area, they have an important role for migratory birds, as well as for crop production and as a water reserve for local people. The continents with the greatest areas of inland water bodies are Asia, Africa and South America (Figure 13).

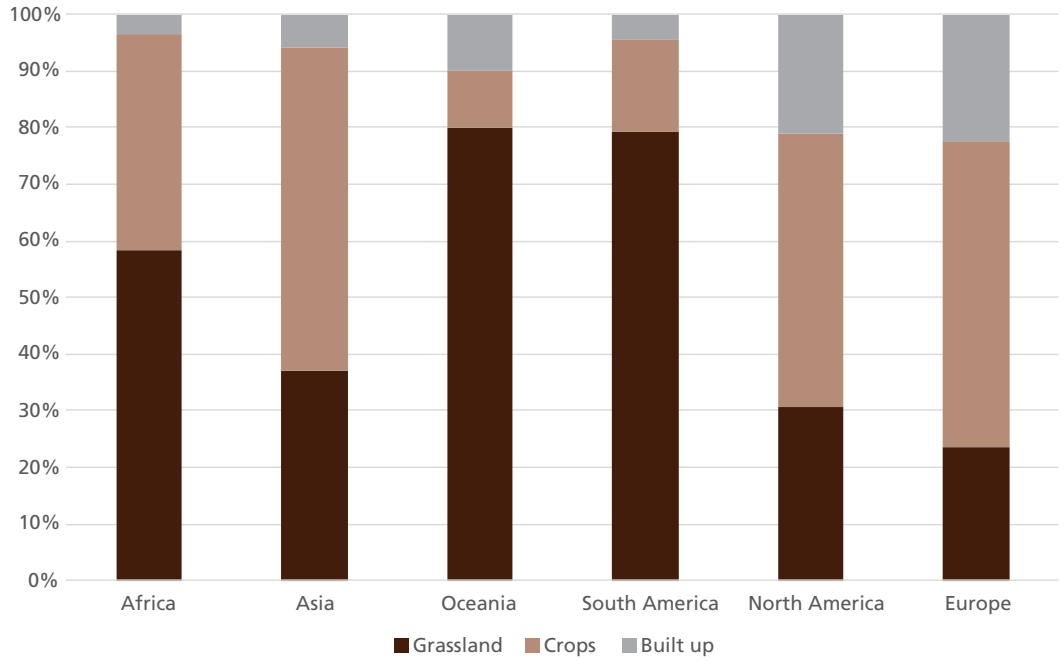
FIGURE 13. Distribution of inland water bodies in "presumed drylands" among continents ('000 ha)



2.8 TREES OUTSIDE FORESTS

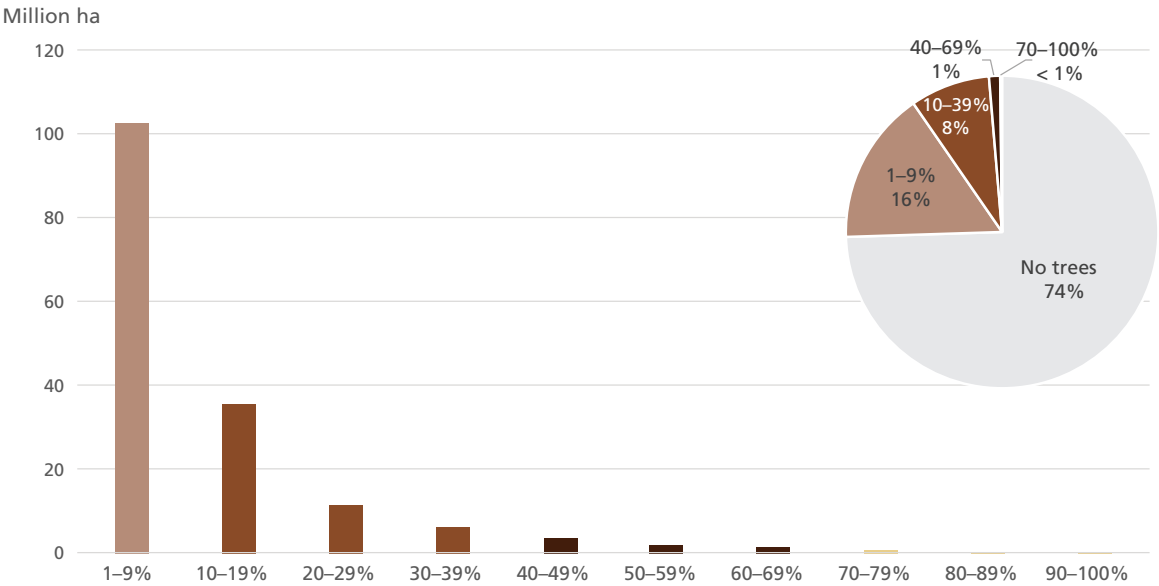
Globally, trees outside forests in "presumed drylands", defined as trees in non-forest land, are found on 57 percent of the grassland area (94 million hectares) and 34 percent of cropland (56 million hectares). In Africa and South America, approximately 58 percent and 79 percent of trees outside forests, respectively, are found in grasslands (Figure 14).

FIGURE 14. Distribution of trees outside forest in "presumed drylands" by land-use category



In "presumed drylands", most of other land has no trees (74 percent). The majority of other land with trees has a canopy cover between 1 and 9 percent (16 percent) and the remaining 9 percent has a tree cover above 10 percent (Figure 15).

FIGURE 15. Tree canopy cover in other land in "presumed drylands"

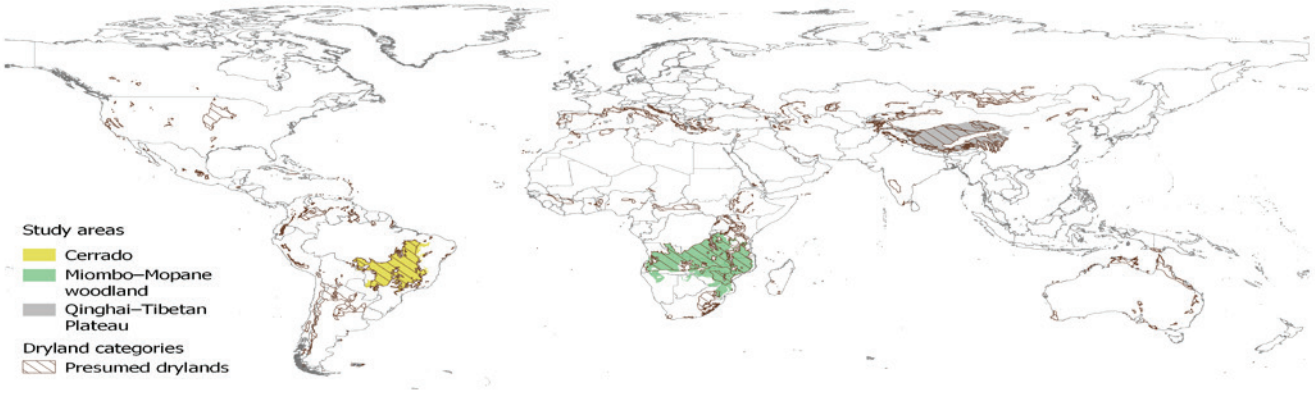


This chapter provided a summary of data and information on the world´s "presumed drylands", which are distributed among all the continents with a total area of 1 075 million hectares and containing 322 million hectares of forest. However, as shown clearly, most "presumed dryland" areas are found in Africa, South America and Asia. The next chapter of this assessment focuses within these regions on the areas where "presumed drylands" are most abundant, using a multidisciplinary approach. The three study areas – the Cerrado in Brazil, Miombo–Mopane woodlands in southern Africa, and the Qinghai–Tibetan Plateau in China – are investigated using remote sensing data combined with an in-depth literature review, ground-truthing fieldwork and stakeholder consultations to assess their status, challenges and opportunities so as to avoid or reverse land degradation, and enable restoration of the native ecosystems.

3. State of "presumed drylands" in the Cerrado, Miombo–Mopane woodlands and Qinghai–Tibetan Plateau: challenges and current practices

In the present chapter, we focus on the state of "presumed drylands", the challenges they face, as well as the potential opportunities and practices that can help achieve land degradation neutrality (LDN). As "presumed drylands" are considerably less extensive than the other dryland categories and unevenly spread, the analysis in this chapter does not encompass all aspects presented in the global drylands assessment (FAO, 2019) and only addresses those areas where "presumed drylands" are most abundant, i.e. the Cerrado ecoregion in South America, the Miombo–Mopane woodlands in Africa and the Qinghai–Tibetan Plateau in Asia. "Presumed drylands" in the three study areas cover 592 million hectares and all together constitute slightly over 55 percent of all "presumed drylands" globally (Figure 16). As such they represent a vital resource base for millions of people and need to be maintained in a good ecological state in order to ensure future livelihoods. In particular, forest, other wooded land and trees are present on a large area of "presumed drylands", thus providing opportunities for using agrosilvopastoral systems and sustainable practices that support LDN.

FIGURE 16: Global map of the distribution of "presumed drylands" across the Earth's land surface. In colour are the three regions addressed in this assessment



Source: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001

3.1 "PRESUMED DRYLANDS" IN THE CERRADO

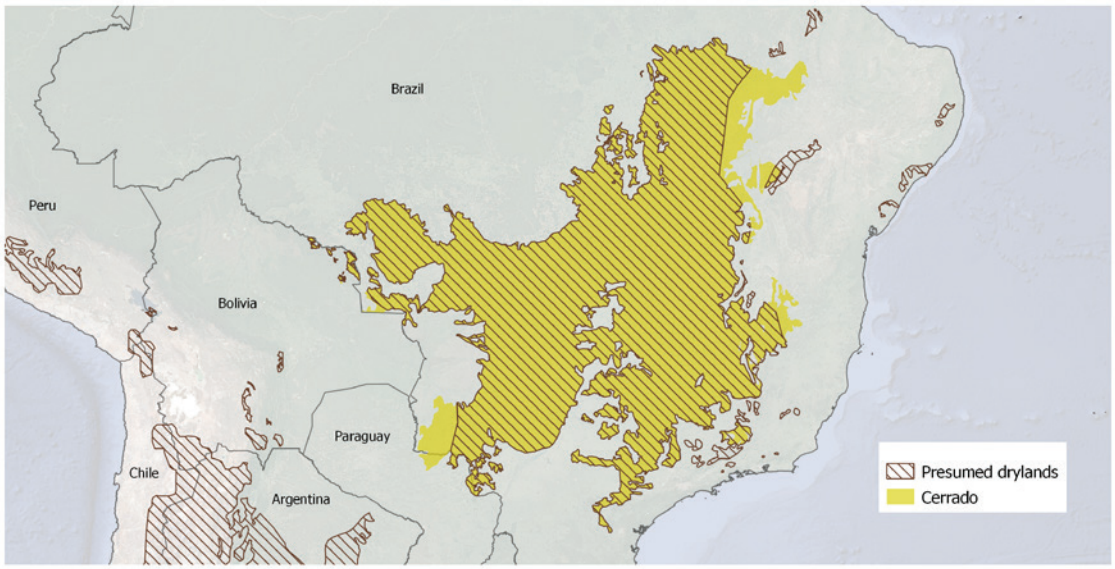
KEY MESSAGES

- "Presumed drylands" in the Cerrado cover 174 million hectares.
- Forests cover 45 percent of "presumed drylands" area in the Cerrado, while grasslands cover 27 percent, cropland 16 percent and other wooded land 10 percent.
- "Presumed dryland" forests in the Cerrado are predominantly natural broadleaved forests (89 percent) and crops are grown on mostly non-irrigated cropland (83 percent).
- In the Cerrado, 56 percent of "presumed dryland" forest has a dense canopy cover of 70–100 percent, while other wooded land is only scarcely covered by trees. Trees outside forests are found on 40 percent of the other land (with scarce canopy cover).
- The Cerrado is one of the richest and most diverse savannas in the world, with high diversity of plants, birds, fishes, reptiles and amphibians. However, many of them are threatened by ongoing land use changes and degradation.
- The Cerrado's ecosystems support the livelihoods and well-being of many people, both by providing ecosystem services and rich agricultural areas for food production.
- Increased demand for food, land use changes, deforestation, excessive use of fertilizers, infrastructure development, introduction of non-native grasses and changes in the fire regime are the main drivers of land degradation in the Cerrado, with climate change representing also a significant contributing factor.
- Land cover changes increase regional temperatures, as well as the frequency and intensity of droughts, and may lead to longer dry seasons, which in turn exacerbate the impact on vegetation and biodiversity. Likewise, more frequent intense fires cause not only damage to flora and fauna, but also accelerate nutrient leaching.
- The primary productivity of plants suffers due to increases in temperature and changes in water availability. This is particularly important for products such as soy, as it is negatively impacting agricultural production.
- Agroforestry systems lead to better conditions for cattle rearing and thus increase productivity, while providing additional benefits such as timber, fruits, improved microclimates and soil fertility, or address aesthetic considerations. Agroforestry also contributes to climate change mitigation through carbon sequestration by trees and carbon storage in soils.
- Other approaches contributing to LDN in the Cerrado include sustainable land management practices, restoration and conservation, as well as fire management.
- Policy factors are crucial in the management, restoration and conservation of the Cerrado. Particularly in regard to fire management, fire suppression policies have had negative consequences for the fire regimes in the region. Initiatives launched by the Brazilian government to promote the proper use of prescribed fires have been beneficial and reduced conflicts.

3.1.1 The Cerrado: general information, biodiversity and ecosystem services

Most of the Cerrado study area is found in Brazil and in particular in the federal states of Goiás, Minas Gerais, Mato Grosso do Sul, Tocantins and Maranhão. Occupying 21 percent of Brazil's land area, geographically the Cerrado extends from 5° N to about 25° S, with small incursions in the west into Bolivia and Paraguay (Figure 17). It is located between the more forested areas of the Amazon and the Atlantic Forest on the coast. The Cerrado has a wet seasonal climate, with marked seasonality characterized by dry winters and a rainy season between October and April (Colli, Vieira and Dianese, 2020; Bustamante *et al.*, 2012). Annual precipitation ranges from 1 300 to 2 300 mm (Franco *et al.*, 2014), with up to 90 percent of precipitation falling in the rainy season between October and April (Hunke *et al.*, 2015). The Cerrado's soils are among the oldest on Earth and are thus deeply weathered with low fertility (Hunke *et al.*, 2015).

FIGURE 17: Coverage of "presumed drylands" in the Cerrado study area



Source: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001

The study area is characterized by a highly heterogeneous landscape due to its complex topography and geological history, and is covered by three major types of habitats: grasslands, savanna and forests (Colli, Vieira and Dianese, 2020). The vegetation structure in the landscape varies greatly, ranging from deeply rooted savanna woodlands and evergreen gallery forests, through less arboreal formations with shrubs and scattered trees to almost treeless grasslands (Franco *et al.*, 2014; Hunke *et al.*, 2015). The herbaceous component is largely either dead or dormant until the wet season arrives. On the other hand, the woody vegetation can produce leaves, flowers and fruits during the dry season, as it has access to moisture in deeper layers of the soil (Hunke *et al.*, 2015). As in other savannas, intense and rapid surface fires are common in the Cerrado and many species are adapted to periodic burning (Franco *et al.*, 2014). Fire affects vegetation dynamics and nutrient cycles and is thus recognized for its ecological importance in the Cerrado.

The Cerrado region is one of the richest and most diverse savannas in the world (Lewinsohn and Prado, 2005) and is considered an endangered ecoregion (Hoekstra *et al.*, 2005), a biodiversity hotspot (Mittermeier, 2004), one of the global 200 ecoregions (Olson and Dinerstein, 2002) and is part of the megadiverse country of Brazil (Brooks *et al.*, 2006). Furthermore, the Cerrado has the highest plant diversity among tropical savannas with around 12 000 species of flowering plants (Bustamante *et al.*, 2012). Species richness of birds (837 species), fish (1 200), reptiles (184) and amphibians (113) is very high, while diversity of mammals is relatively low, with only 199 species (CGEE, 2016; Klink and Machado, 2005; Marinho-Filho, Rodrigues and Juarez, 2002). The number of invertebrate species in the Cerrado is estimated at over 90 000 (Klink and Machado, 2005). In addition, the Cerrado has one of the highest levels of plant endemism in the world (Fernandes *et al.*, 2018). An important aspect of the Cerrado's vegetation is not only its high biodiversity of tree species, but also the coexistence of trees, shrubs and the herbaceous layer (Ratter, Bridgewater and Ribeiro, 2003b; Castro *et al.*, 1999b). Indeed, any hectare of the Cerrado can have up to 70 tree species, with a similar number of shrub species. However, the region's biodiversity is still relatively poorly known, with potentially many species yet to be discovered (Colli, Vieira and Dianese, 2020).

Besides being an important area for biodiversity, the Cerrado's ecosystems support the livelihoods and well-being of many people, both by providing rich agricultural areas for food production and by delivering ecosystem services, for example, indigenous wild fruits (Colli, Vieira and Dianese, 2020). The Cerrado's woodlands also supply valuable sources of firewood and many different non-wood forest products besides fruits, such as honey, leaves, roots and seeds (de Souza e Lira *et al.*, 2020). Agricultural producers in the Cerrado range from a large number of relatively small farms below 100 hectares, to large farms of over 20 000 hectares combining cattle and crop production

(Nair *et al.*, 2011). The Cerrado's soils constitute the largest carbon stock in the Cerrado, as 70 percent of total carbon stocks is found in soil organic matter (Bustamante *et al.*, 2012). Among the Brazilian biomes, the Cerrado has one of the highest belowground to aboveground biomass ratios (Zimbres *et al.*, 2020). The Cerrado is also a vital supplier of water for a large area of Brazil (Rekow, 2019b). Lastly, the biodiversity of riparian and gallery forests plays an important role in controlling stream chemistry in the Cerrado and contributes to improving water quality through increasing soil porosity and facilitating higher soil infiltration rates (Bustamante *et al.*, 2012; Nobrega *et al.*, 2020).

3.1.2 Land use and vegetation in the "presumed drylands" of the Cerrado

In the Cerrado, "presumed drylands" comprise almost 174 million hectares (Figure 17). The analysis has shown that forests cover 45 percent of the area of "presumed drylands", while grasslands cover 27 percent, cropland 16 percent and other wooded land 10 percent (Figure 18). The remaining land is classified as barren land, built-up areas and inland water bodies, all together covering around 2 percent of the area of "presumed drylands" in the Cerrado ecoregion.

Presumed dryland forests are predominantly (89 percent) natural broadleaved forests, while about 6 percent are riparian and gallery forests. The assessment did not identify the vegetation cover type for 1 percent of total forest. Crops are grown in mostly non-irrigated cropland (83 percent), followed by irrigated cropland (15 percent), while some perennial crops are also cultivated (2 percent; Table 6 and Table 7). Inland water bodies consist mostly of permanent rivers or inner deltas (59 percent) and permanent lakes or pools (34 percent), while seasonal lakes cover only 2 percent of the area.

TABLE 5:
Type of forest vegetation in "presumed drylands" in the Cerrado

Vegetation type	,000 ha	%
Natural forest		
Broadleaved	70 005	89
Riparian and gallery forest	4 934	6
Coniferous	253	0
Mixed broadleaved and coniferous	76	0
Other/not identified	531	1
Planted forest	2 682	3
Total	78 481	100

TABLE 6:
Land use and land use type coverage in the Cerrado

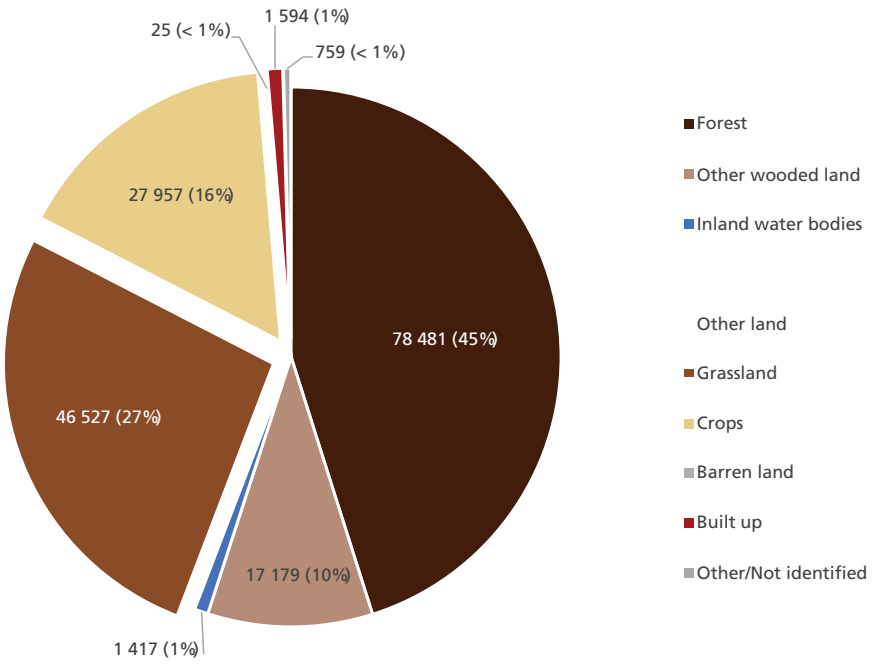
Land use	Land Use Type	,000 ha	%
Grassland		46 527	100
Cropland		27 957	100
	Irrigated crops	4 099	15
	Non-irrigated cropland	23 200	83
	Perennial crops (palms, orchards, others)	658	2
Barren land		25	100
Built up		1 594	100
	Village and urban	987	62
	Infrastructure and built up	607	38
Other/not identified		759	100

The vegetation cover in other wooded land is mainly dominated by shrubland (49 percent) and grassland with trees and shrubs (37 percent), while grasslands with shrubs cover 6 percent of the total area (Table 8). The assessment did not identify the vegetation cover type for 8 percent of other wooded land.

TABLE 7:
Main vegetation types in other wooded land in the Cerrado

Vegetation type	,000 ha	%
Grassland with shrubs	1 088	6
Grassland with trees and shrubs	6 300	37
Shrubland	8 450	49
Other/not identified	1 341	8
Total	17 179	100

FIGURE 18. Distribution of land uses in "presumed drylands" ('000 ha) in the Cerrado study area



The assessment shows that 56 percent of presumed dryland forest has a dense canopy cover of 70 to 100 percent, and less than 1 percent of the forest has a canopy cover in the lowest range of 1 to 9 percent (Figure 19). In contrast, other wooded land is scarcely covered by trees: 79 percent has a canopy cover of 1 to 9 percent, while 21 percent has no tree cover (consisting only of bushes and shrubs). In the presumed dryland forest, there is almost no shrub cover, while shrub cover is relatively abundant in other wooded land (Figure 20). Trees outside forests are found on 40 percent of the other land, though most of this land has a canopy cover of only 1 to 9 percent (Figure 21).

3.1.3 Land degradation in the Cerrado:

Human impacts and land use change

Since the 1960s, the Cerrado region has been subject to intense agricultural expansion (Nair *et al.*, 2011), leading to rapid habitat loss due to large-scale conversion of native areas into agricultural land and changes in fire regimes (Bustamante *et al.*, 2012). To date, over half of the Cerrado area has been converted to pastures (with grasses dominated by *Brachiaria* species), croplands or planted forests, and deforestation rates have been higher than in the Amazon rainforest (Klink

FIGURE 19. Tree canopy cover in other land in "presumed drylands"

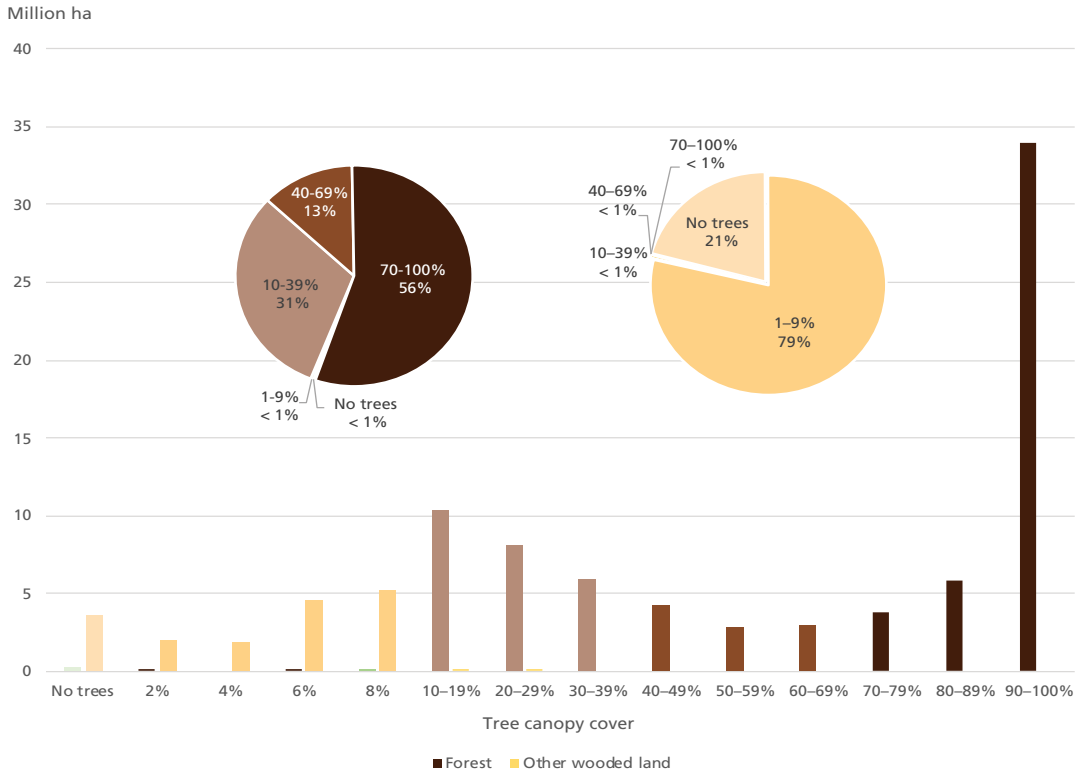
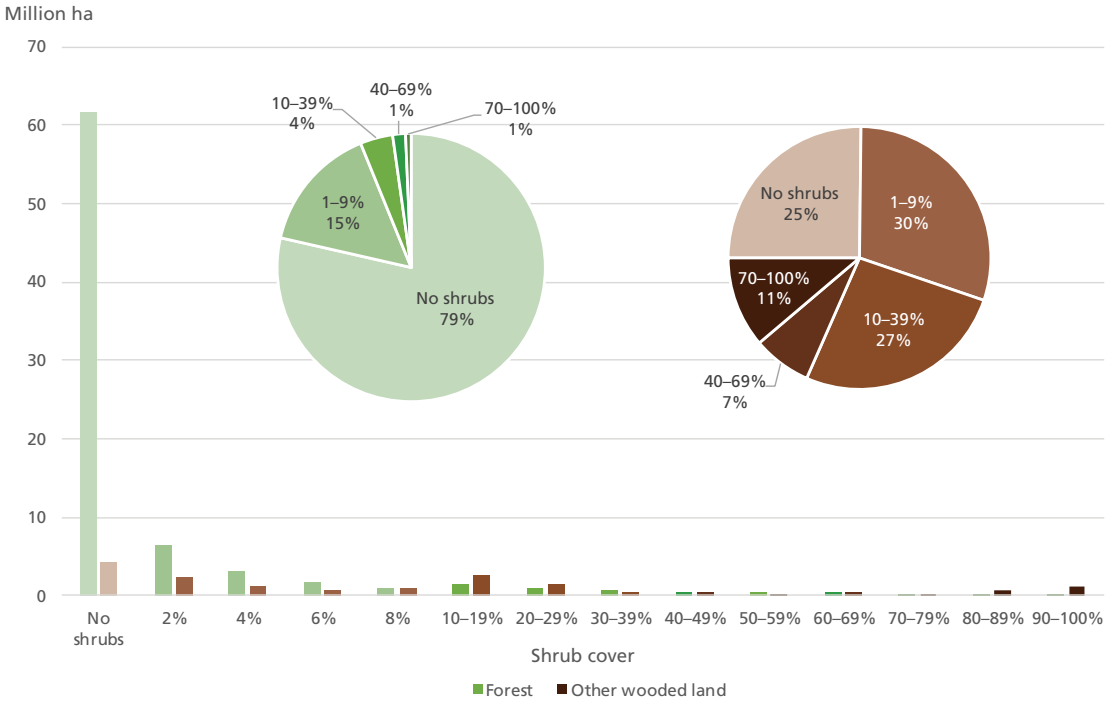
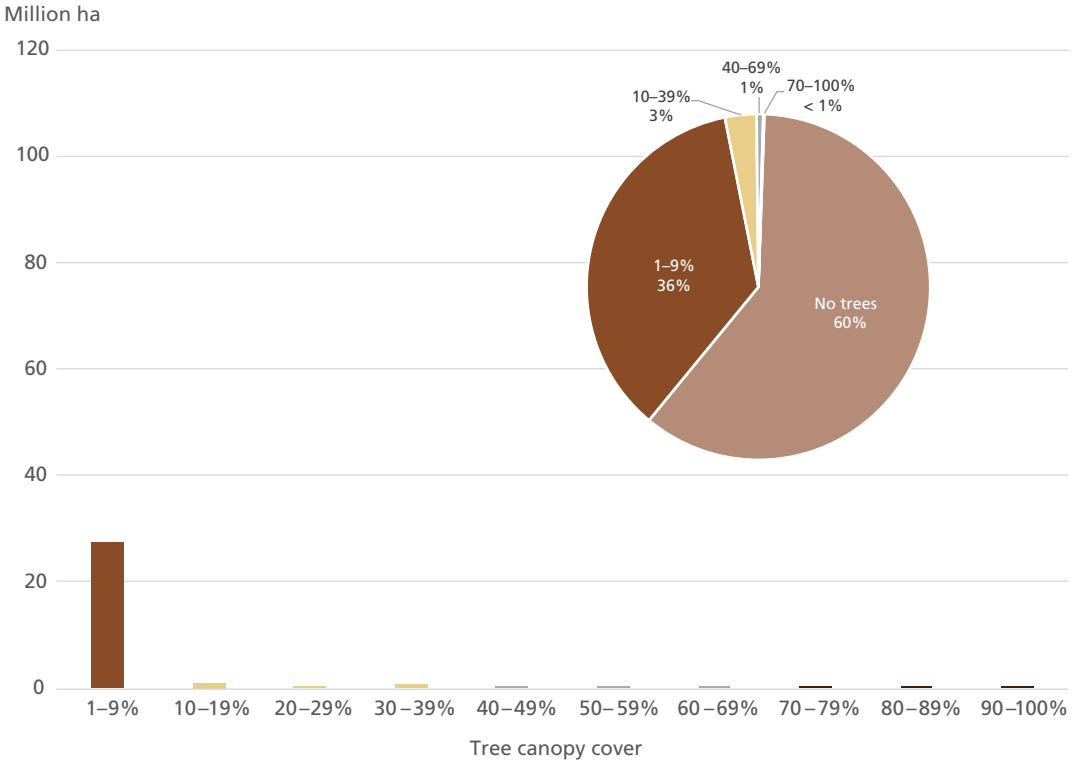


FIGURE 20. Shrub cover in forest and other wooded land in "presumed drylands" of the Cerrado



and Machado, 2005; Colli, Vieira and Dianese, 2020; Sano *et al.*, 2010; Arvor *et al.*, 2012) (Box 3). For example, it has been estimated that the Cerrado lost 265 595 square kilometres of its natural vegetation cover between 1990 and 2010 (Beuchle *et al.*, 2015). To address the low soil fertility, a limiting factor for agriculture, the land has been limed to a great extent (Yamada, 2005). There was also widespread agrochemical applications of fertilisers and pesticides in order to allow large scale and successful cultivation of tropically-adapted cash crops, which also contributed to the pollution

FIGURE 21. Tree canopy cover in other land in "presumed drylands" of the Cerrado



Box 3
Some variables for which data were collected

- To date over 50 percent of the native Cerrado vegetation has been lost.
- Genetic diversity of plants in the Cerrado decreases from north to south and is higher in areas with a lower human development index.
- At least 137 animals in the Cerrado are threatened with extinction, which is particularly alarming for rare species that require large, connected habitats, such as the giant armadillo (*Priodontes maximus*).
- While the Cerrado holds about one third of Brazil's biodiversity, only 8.3 percent of its area is protected; 6.5 percent if only areas covered by native vegetation are considered; 3 percent if only strictly protected areas are counted.
- Deforestation rates in the protected areas of sustainable use (corresponding to IUCN categories IV to VI) are similar to the rates outside protected areas, suggesting lack of proper biodiversity protection.

Sources: Klink and Machado (2005); Colli, Vieira and Dianese (2020); Bustamante +. (2012); Francoso *et al.* (2015); Reynolds *et al.* (2016); Hillsdon, 2018; TNC, 2019

of rivers (Hunke *et al.*, 2015). Deforestation in the Cerrado has resulted in the loss of natural vegetation cover, increased soil loss through erosion and increased albedo, and land degradation (Bianchi and Haig, 2013; Garcia and Ballester, 2016; Trabaquini *et al.*, 2012). A recent study from the Cerrado has found that around 39 percent of the region's pastures are already degraded (Pereira *et al.*, 2018). Besides agricultural expansion and deforestation, the development of infrastructure has also greatly contributed to habitat loss (Colli, Vieira and Dianese, 2020; De Marco *et al.*, 2020).

Brazil is currently the top producer of many commodities, including soy, sugar cane and coffee, as well as second and third globally in beef and maize production, respectively (USDA, 2020; Coe *et al.*, 2017). In recent decades, the Cerrado has become the largest agricultural frontier in the country, with the expansion of genetically modified monoculture of soy at a large scale and cattle ranching

being the primary drivers of habitat conversion, resulting in the loss of approximately half its native vegetation (Hillsdon, 2018; TNC, 2019). Over 55 percent of the cattle production in Brazil takes place in the Cerrado (Pereira *et al.*, 2018), and 51 percent of Brazil's soy area is already located in the Cerrado (ABIOVE, 2020). Because the production of cash crops and cattle is so lucrative, it is expected that the rapid degradation of the Cerrado will continue (Klink and Machado, 2005). The growing global demand for soy products in particular represents a critical risk to the remaining native Cerrado vegetation, with negative impacts on ecosystem service provision, including carbon storage and sequestration and moisture recycling and regulation (O'Connor and Kuyler, 2009). Certain projections indicate that deforestation of this area will increase by 13.5 percent per decade until 2050 (Hunke *et al.*, 2015).

In addition to agricultural production, planted forests, particularly plantations of fast-growing non-native trees such as eucalyptus hybrids (*Eucalyptus* spp.) and pines (*Pinus* spp.) have gained popularity in the last two decades.

Fire is a very important element in the Cerrado's ecosystem and it is well-adjusted to regular low intensity fires that maintain ecosystem structure, biodiversity and functioning (Durigan and Ratter, 2016). Indigenous people have been using fire as a management tool in the Cerrado for thousands of years in cultivation, hunting, land clearing and honey production (Mistry *et al.*, 2005). This has led to the evolution of a mosaic of different (burned and unburned) patches in the landscape, creating natural firebreaks, and hence a situation where some areas burn frequently, while others rarely burn (Mistry *et al.*, 2005). Consequently, traditional management by cattle ranchers has deliberately aimed at protecting fire-sensitive vegetation and preventing devastating high-intensity and large-scale wildfires (Durigan and Ratter, 2016; Eloy *et al.*, 2019). However, due to the misuse of fire for pasture management and deforestation in the twentieth century, fire suppression policies have been implemented. These policies, in turn, have led to the cessation of natural fires.

While prescribed fires for managing nature reserves are allowed (according to Federal Decree No. 97635 of 10 April 1989), in reality, few official permits are given for this purpose (Mistry *et al.*, 2005). Similarly, while fire can be used for agricultural purposes (according to Ministerial Decree No. 229/75 of 7 May 1975), the rules for its use are complicated and implementation is costly, hampering its proper use (Mistry *et al.*, 2005). Therefore, fire cessation has led to fuel accumulation and increased the occurrence of large-scale devastating late dry season wildfires in the Cerrado. Moreover, illegal and often inappropriate fires for agricultural purposes have been used more frequently (Pivello, 2011; Mistry *et al.*, 2005). This has resulted in the homogenization of the Cerrado's mosaic of ecosystems, transforming many of the original grassland areas into forest, with negative consequences for the Cerrado's biodiversity. While forest encroachment due to fire suppression creates a higher diversity of tree species and increased carbon stocks (Pellegrini *et al.*, 2016), it likewise decreases the diversity of shrubs and herbaceous plants due to limited light availability under tree cover (Abreu *et al.*, 2017). Similar impacts can be expected for some animal species, as many of them are dependent on the original vegetation structure. For example, Abreu *et al.* (2017), in their study at the Santa Barbara Ecological Station, located near the southeastern edge of the Cerrado region, have noted that the species richness of ants decreased by 86 percent between 1986 and 2015 due to forest encroachment.

3.1.4 Consequences of land use changes and degradation

The land cover changes in the Cerrado have transformed this region into a complex mosaic of grasslands, intensive cropland and pasture, dry deciduous forests and woodlands, and humid rainforest, with important consequences for the local and regional climate (Coe *et al.*, 2017). According to a study by Campos and Chaves (2020), based on data from the National Water and Sanitation Agency (ANA) of Brazil, the conversion of 86 million hectares of native vegetation into pasture or cropland throughout Brazil between 1977 and 2010 (about 2.6 million hectares/year) resulted in a 125 mm decrease (8.5 percent) in precipitation. Due to the changes in evapotranspiration, the sensible heat flux increases, which may lead to an increase in annual surface temperatures by as much as 5 °C (Coe *et al.*, 2017), altering the local microclimate in many places in the Cerrado and contributing to regional climate change (Hunke *et al.*, 2015). Moreover, climate modelling

experiments have shown that preserving the remnant Cerrado is essential not only to climate stability in the Cerrado, but also the Amazon downwind (Malhado, Pires and Costa, 2010), as air masses moving westward over the Cerrado transport evapotranspired water over the Amazon Basin (Spracklen, Arnold and Taylor, 2012). In addition, deforestation of the Cerrado is a significant source of greenhouse gas emissions contributing to global climate change. For example, between 2003 and 2013, land conversion from forest to cropland accounted for 29 percent of the emissions in the Cerrado (Noojipady *et al.*, 2017).

Rodrigues *et al.* (2020) predict that both the frequency and intensity of droughts will increase in the future in the Cerrado. At the same time, heavy rainfall events are likely to increase in the Cerrado, particularly in the south-central region (IPCC, 2013; Marengo *et al.*, 2010), causing greater leaching of nutrients (Bustamante *et al.*, 2012).

With the intensification of agricultural activities and changes in the fire regime, these anthropogenic processes are increasing nutrients, such as nitrogen and phosphorus, in the Cerrado's natural ecosystems, particularly impacting its waters (Tilman *et al.*, 2002; Bustamante *et al.*, 2012). Many studies from the Cerrado found pesticides in its ground and surface waters (Dores *et al.*, 2008; Casara *et al.*, 2012), showing that this is a widespread problem in the region. Likewise, a longer dry season and intensification of fires can hasten the impoverishment of soils. Finally, the primary productivity of plants may suffer due to increases in temperature and changes in water availability, negatively impacting not only natural ecosystems but also agricultural production (Bustamante *et al.*, 2012).

3.1.5 Opportunities and best practices to contribute to land degradation neutrality

Different approaches and practices that can help mitigate and avoid land degradation and contribute to achieving LDN have been applied in the Cerrado, such as various sustainable agrosilvopastoral systems, fire management approaches and restoration activities.

3.1.5.1 Agroforestry systems

Silvopastoral systems are the most common agroforestry systems in the Cerrado.[3] In 2011, it was estimated that such systems covered 14 000 hectares in the Cerrado (Nair *et al.*, 2011). In 2018, silvopastoral systems covered as much as 2 million hectares in Brazil (Santos *et al.*, 2018), but no up-to-date data on the extent of such systems in the Cerrado could be found.

Many studies from the Cerrado show that integrating cattle or crops with native trees species into silvopastoral systems delivers many benefits, in addition to supporting cattle rearing. These include regulating ecosystem services, such as mitigating soil compaction and erosion, improving nutrient cycling and ameliorating soil acidity, and providing shade that helps maintain soil moisture for longer periods, as well as provisioning ecosystem services such as fodder, firewood, timber, medicinal plants and fruits, and monetary benefits to farmers from forest resources (Lima, Scariot and Giroldo, 2017; Reis *et al.*, 2010; Nair *et al.*, 2011; Paciullo *et al.*, 2011; Martinelli *et al.*, 2019). Agroforestry is also recognized as an activity for climate change mitigation (Gama-Rodrigues *et al.*, 2010; IPCC 2019), and its role in creating carbon sinks in the Cerrado has been confirmed by different studies (Tonucci *et al.*, 2017). For example, a study by Martinelli *et al.* (2019), investigating agroforestry systems within the GEF-funded project 'Integrated Watershed Management and Protection' in the Formoso River Basin, showed the significant capacity of agroforestry to sequester carbon, ranging from 263 to 496 tCO_2eq/hectare, depending on the type of system. Likewise, a study by Gama-Rodrigues *et al.* (2010), investigating carbon storage in cacao (*Theobroma cacao L.*) agroforestry systems, showed that they accumulate high amounts of organic carbon in the soil due to continuous deposition of plant residues from both the cacao and the shade species and relatively limited removal of carbon via harvested products. In general, agroforestry systems have a higher potential than cropland or pasture alone to sequester carbon in soils because of the higher levels of organic matter in the system (Sanchez, 2000; Kirby and Potvin, 2007) (Box 4).

[3] There are different agroforestry systems in Cerrado – see the technical handbook by Miccolis, A., Peneireiro, F.M., Marques, H.R., Vieira, D.L.M., Hoffmann, M.R., Rehder, T. & Pereira, A.V.B. 2016. *Agroforestry systems for ecosystem restoration. How to reconcile conservation and production. Options for Brazil's Cerrado and Caatinga biomes. Technical guidebook*. Instituto Sociedade, População e Natureza – ISPN/World Agroforestry Centre.). Agroforestry to heal damaged land from fires – Forests, Trees and Agroforestry (foreststreesagroforestry.org)

Box 4
Integrated crop–livestock–forestry (ICLF) systems

ICLF are one example of agroforestry initiatives in Brazil, including in the Cerrado, which seek to integrate the production of food, fibre, energy and timber and non-timber forest products in the same area. At the same time, they help in maintaining forest cover and restoring degraded areas, and contributing to creating employment opportunities and improving social conditions for rural communities. Currently, complete ICLF systems, that is, those integrating crops, livestock and forests, are still few in the Cerrado, but work is ongoing for their development.

Another example is the ABC (Low Carbon Agriculture) programme of the Ministry of Agriculture implemented in many regions in Brazil, including the Cerrado.The aim is to encourage the adoption of sustainable production systems that ensure the reduction of greenhouse gas (GHG) emissions and simultaneously increase the income of producers through, among others, use of ICLF and agroforestry systems. These systems can be complemented by ABC, which includes the application of no-tillage measures and biological nitrogen fixation approaches to promote low-carbon agricultural production in the Cerrado.

3.1.5.2 Conservation agriculture

Conservation agriculture (CA) approaches include a range of different cropping systems based on three common principles, namely: 1) the reduction of soil tillage; 2) crop rotation diversification; and 3) soil protection by organic residues (Scopel *et al.*, 2013). Two main CA systems are found in the Cerrado. One is a CA system with two crops in succession annually, with one commercial crop (such as rice, soy or maize) and a second crop either as a cover crop or grown for commercial purposes (such as millet, maize or sorghum). The other is a system with one commercial crop intercropped with a cover crop producing extra biomass at the end of the rainy season to be grazed or used as green manure (for instance from the genera *Brachiaria* – i.e. grasses, or the herbaceous legumes – *Cajanus*, *Stylosanthes*, *Crotalaria*). The latter one is often applied with notable additions of fertilizers by large-scale farmers, while small-scale farmers usually apply very few chemicals (Scopel *et al.*, 2013).

In the Cerrado, using no-tillage CA significantly reduces the rate of soil erosion (Scopel *et al.*, 2013) and losses of soil organic carbon (Batlle-Bayer, Batjes and Bindraban, 2010), while increasing soil macrofauna (Blanchart *et al.*, 2007). The WOCAT (World Overview of Conservation Approaches and Technologies) database also shows an experiment in Mato Grosso State that using minimum tillage practices not only reduced erosion, but also helped to minimise carbon releases into the atmosphere.[4] In addition, several studies have demonstrated that CA systems in the Cerrado have higher carbon stocks than conventional tillage systems (Roscoe and Buurman, 2003; Bernoux *et al.*, 2006; Bustamante *et al.*, 2006). Another approach tested in the Cerrado and included in the WOCAT database was adding organic matter to increase soil carbon.[5] As such, experiments in Mato Grosso State clearly showed that the addition of industrial organic waste significantly increased the soil organic carbon content.

3.1.5.3 Fire management

Fire is an important determinant shaping the ecological conditions in the Cerrado, especially since the ecoregion is a fire-adapted ecosystem. Using traditional fire management, where some areas are regularly burned to prevent high intensity wildfires, can thus be an opportunity for sustainable management of large areas of the Cerrado.

Recently, some initiatives have been launched by the Brazilian government and funded by GIZ to promote the proper use of prescribed fires, such as the Cerrado-Jalapão project where[6] stakeholders with traditional knowledge on fire management were consulted, resulting in decreased conflicts regarding fires in the area (Eloy *et al.*, 2019). A follow-up study from this initiative has

[4] https://qcat.wocat.net/en/wocat/technologies/view/technologies_1270/

[5] https://qcat.wocat.net/en/wocat/technologies/view/technologies_1250/#, and https://qcat.wocat.net/en/wocat/approaches/view/approaches_2541/

[6] https://qcat.wocat.net/en/wocat/technologies/view/technologies_1250/#, and https://qcat.wocat.net/en/wocat/approaches/view/approaches_2541/

shown that under traditional management, i.e. using regular fire regimes, less damage was caused and smaller areas were burned, in comparison to those areas managed by the government being subject to large, biennial, late dry season wildfires (Eloy *et al.*, 2019).

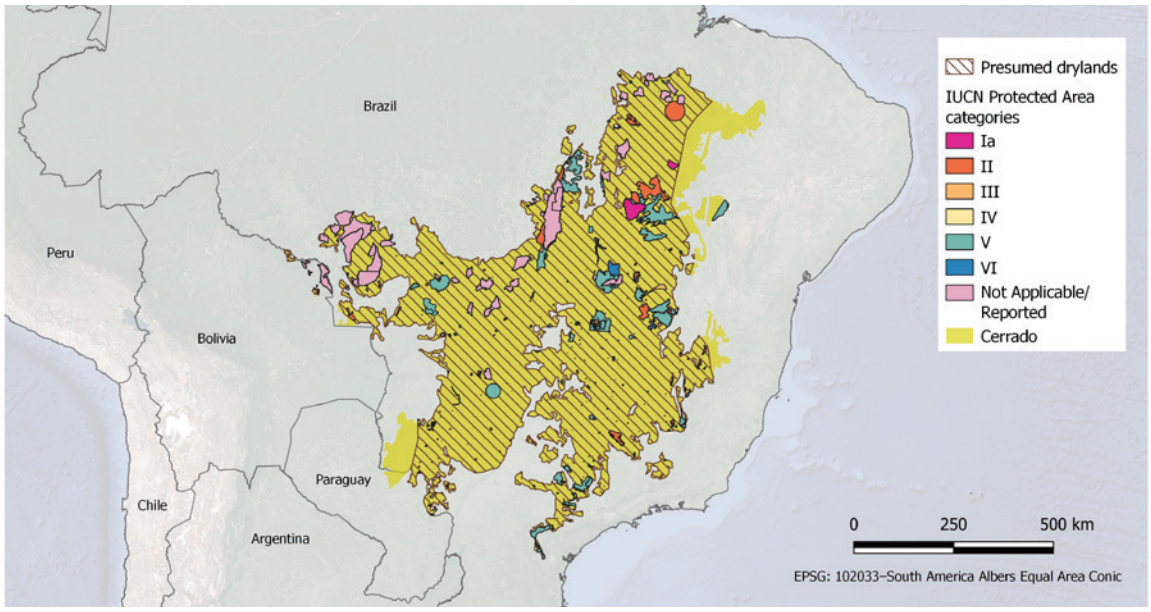
3.1.5.4 Restoration and conservation

Most commonly, natural regeneration should be used as a way to restore degraded areas in the Cerrado. However, various restoration initiatives have also taken place in the Cerrado (Guerra *et al.*, 2020), including planting seedlings, direct seeding and enrichment planting of species that do not colonize sites of natural regeneration (Brancalion *et al.*, 2019).

According to the 2012 Brazilian Forest Code,[7] farmers are obliged to restore degraded lands on conservation set-asides (required for all rural properties which creates an opportunity to adopt land management practices that benefit wildlife), usually using some form of agroforestry system (see section 3.1.6.1). This is seen as a win–win situation that both improves the conservation value of such areas and provides benefits to the farmers (Miccolis *et al.*, 2019).

Historically, relating to protection, the first conservation units in the Cerrado were created in 1949; the oldest being the Silvânia National Forest, and many more were established in the first decade of the twentieth century.

FIGURE 22: Protected areas in the Cerrado according to the IUCN classification
***Sources*:** UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001; IUCN and UNEP-WCMC, 2021



More recent conservation initiatives have also taken place in the Cerrado. For example, World Wide Fund for Nature (WWF), Conservation International and The Nature Conservancy, all have conservation programmes in the region (Klink and Machado, 2005). Their projects usually focus on the creation or expansion of protected areas or establishing biodiversity corridors (for example, Emas–Taquari and Cerrado–Pantanal), but some also aim to improve livelihoods of local indigenous communities, particularly through the promotion of alternative economic activities. Brazil has also engaged in projects aimed at the conservation and development of agricultural areas. In 2013, it adopted the National Integrated Crop-Livestock-Forestry Policy (Martinelli *et al.*, 2019). Through the Low Carbon Agriculture (LCA) Plan and incentives linked to it, Brazil has also promoted the development of numerous silvopastoral systems, rehabilitation of degraded pastures and increasing the area under no-tillage in the Cerrado by providing low-interest loans to farmers adopting sustainable practices (Neate, 2013; Santos *et al.*, 2018).

In terms of protection, the total area of protected areas, both at national level – and international ones, such as Ramsar sites and Biosphere reserves, was slightly below 13 percent in the "presumed drylands" of the Cerrado. When only IUCN categories of protected areas were taken into account, the area in "presumed drylands" was slightly below 8 percent (Figure 22).

[7] https://news.mongabay.com/2019/03/brazils-new-forest-code-puts-vast-areas-of-protected-amazon-forest-at-risk/

Currently, the Cerrado has 323 conservation units, most of them created and managed by state governments (190), followed by the federal government (94) and municipal government (39). However, only 65 conservation units had management plans in 2019.

3.2 "PRESUMED DRYLANDS" IN MIOMBO–MOPANE WOODLANDS

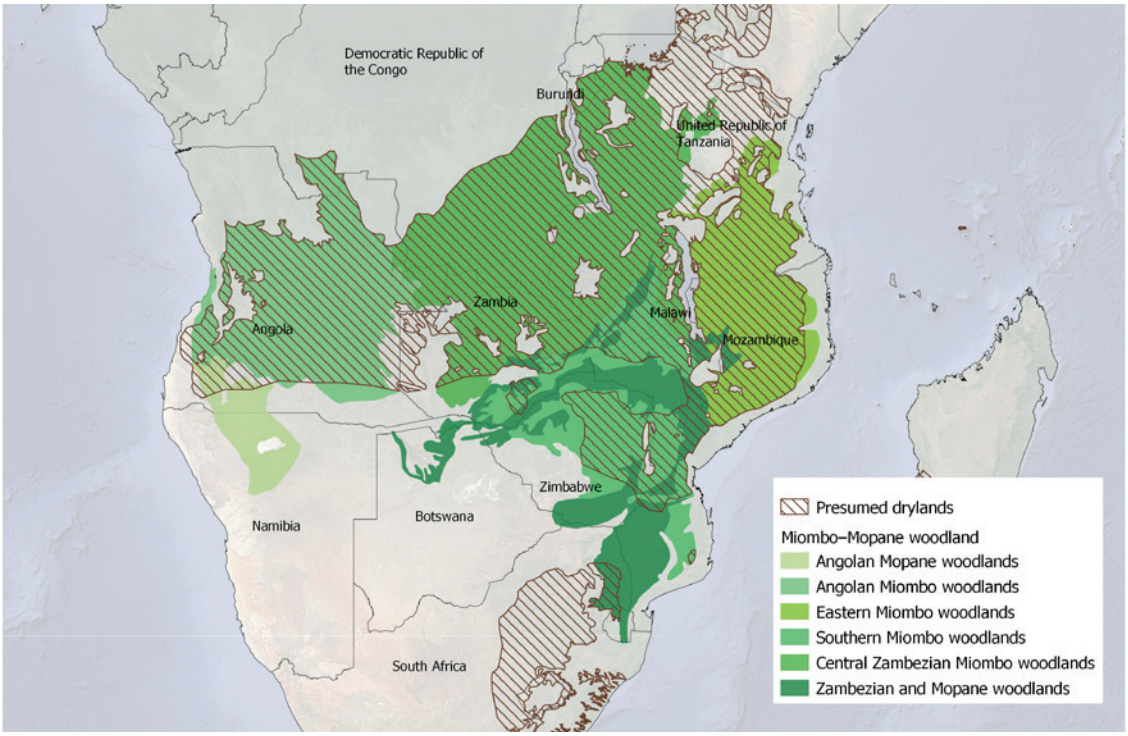
Key messages

- "Presumed drylands" in Miombo–Mopane woodlands cover 265.6 million hectares.
- Forests cover 44 percent of the area of "presumed drylands" in Miombo–Mopane woodlands, while grasslands cover 25 percent, croplands 13 percent and other wooded land 13 percent.
- More than half (55 percent) of "presumed dryland" forests in the Miombo–Mopane woodland area are natural broadleaved forests, followed by mixed broadleaved and coniferous forests (21 percent), coniferous forests (5 percent), and riparian and gallery forests (4 percent).
- 56 percent of "presumed dryland" forest has a dense canopy cover of 70–100 percent. 40 percent of other wooded land has no tree cover, while 30 percent has canopy cover between 10 and 39 percent.
- Trees are present on 53 percent of the land outside forests, with most of the canopy cover below 40 percent.
- The Miombo–Mopane woodland area is characterised by high biodiversity and provides numerous ecosystem services for local communities. Most people live in rural areas and depend on agricultural activities for their livelihoods.
- A growing population, unsustainable farming practices and overgrazing, fuelwood gathering and charcoal production, as well as the emergence of urban markets for products such as charcoal, timber and tobacco are the main drivers of land degradation and deforestation.
- Harvesting biomass, for instance, for fuelwood and charcoal production, affects soil carbon storage and results in changes in the soil chemistry. Habitat fragmentation linked to land use change and infrastructural developments negatively impacts the hydrology and ecological functions of the region, with cascading effects on biodiversity.
- Climate change leads to higher temperatures and more extreme dry and wet seasons, while contributing to water stress, and thus resulting in increased food insecurity. Recurring droughts with high temperatures, high winds and low relative humidity also exacerbate erosion.
- Soil structure degradation, nutrient limitations and low soil organic carbon concentrations are widespread across the region, jeopardising the livelihoods of millions of people dependent on different woodland products and ecosystem services, with particularly negative impacts on women.
- Agroforestry systems, particularly silvopastoral systems and intercropping of food crops with trees, or use of fertilizers are important practices in the "presumed drylands" of the Miombo–Mopane woodland area. Such practices can lead to enhancing agricultural productivity and food security by delivering additional food resources, thus helping agriculture adapt to climate change, as well as sequestering carbon.
- Sustainable land management practices, such as reseeding with nitrogen-fixing species, crop rotation, crop residue retention, minimum soil disturbance or limiting tillage, can all help improve soil structure and infiltration, as well as carbon content, thus mitigating the effects of land degradation and climate change.
- Policies, such as those to strengthen local land tenure, can provide an important base for addressing land degradation in the Miombo–Mopane woodland region, but their implementation remains a challenge.
- Numerous projects and initiatives tackling land degradation and improving local livelihoods have been and are currently being implemented in the region.
- Local communities apply different adaptive strategies, such as using rain corridors or cultivation in sandy rivers in Zimbabwe, or adjusting traditional farming practices to environmental change as carried out by farmers in the United Republic of Tanzania, in order to maintain their livelihoods in the face of increasing impacts from land degradation and climate change. Local knowledge is crucial in these efforts.

3.2.1 Miombo–Mopane woodlands: general information, biodiversity and ecosystem services

Miombo–Mopane woodlands comprise a transboundary region extending from the west coast of Africa in Angola to the east coast in Mozambique and the United Republic of Tanzania. This area can be divided into six ecoregions (Figure 23) and stretches over eight countries: Angola, Burundi, the Democratic Republic of the Congo, Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe. The climate of the Miombo–Mopane woodlands differs depending on location. In general, it is a seasonal climate with a dry and wet season, although many areas have relatively low precipitation. In addition, the soils in many places of the Miombo–Mopane woodland area are infertile and fragile, due to both natural weathering of old mineral-rich rocks and misuse over long periods (Msangi, 2007). The region is covered by a combination of different types of open, seasonally dry, deciduous woodlands, as well as grasslands and bushlands. Fires set by local communities, mostly between July and October, shape the vegetation structure and species composition (Chidumayo, 1997). Burning helps prepare land for cultivation by clearing weeds, or for livestock grazing by controlling tick populations and encouraging the growth of fodder plants (Timberlake and Chidumayo, 2011).

FIGURE 23: Coverage of "presumed drylands" in Miombo–Mopane woodlands



Sources: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001

The Miombo–Mopane woodland area is characterised by high biodiversity and is considered one of the world's five high-biodiversity wilderness areas (HBWAs) according to Mittermeier *et al.* (2003). The region hosts 8 500 species of plants alone and over half of them are endemic to these woodlands (Frost, 1996; Moura *et al.*, 2017). It also hosts a large variety of charismatic large herbivorous mammals such as elephants, hippos, zebras, giraffes, buffalos, white and black rhinos, and primates including baboons, bushbabies and chimpanzees (on the Miombo–Mopane woodland margin), as well as large predators such as leopards, hyaenas, cheetahs and lions (Timberlake and Chidumayo, 2011). Large mammals are the backbone of the tourism industry, an important sector for the region's economy, mostly in the form of trophy hunting and wildlife viewing. There is also a large variety of birds in the area, numbering 938 species, 51 of which are endemic. While they have not been fully quantified, there are, for instance, over 900 species of passerines (i.e. perching birds) recorded. In addition, there are 284 species of reptiles and 130 amphibians, 52 and 25 of them

endemic, respectively, and a large number of invertebrates, which, however, are poorly recorded. One of the important groups of invertebrates is termites. Malawi, for example, has 106 species of termites recorded. It is estimated that the region has over 1 300 species of butterflies, of which at least 90 are endemic (Timberlake and Chidumayo, 2011). While there are no estimates of species in the actual area of "presumed drylands", the numbers for the whole Miombo–Mopane woodlands may be indicative of their species richness, particularly as "presumed drylands" cover most of the Miombo–Mopane area.

Most people in the Miombo–Mopane woodland area live in rural areas and depend on agricultural activities for their livelihoods, with up to 80 percent of the population, for example, in Malawi and Burundi.[8] In Angola, the agrarian sector accounts for 80 percent of the population and 44 percent of formal employment, but contributes to only 10 percent of the country's GDP, as it is grossly underdeveloped.[9] The predominant way of living remains in the form of slash-and-burn farming (Williams *et al.*, 2008) and shifting cultivation with short periods of cropping and longer periods of fallow (Gonçalves *et al.*, 2017). Cattle are the most common livestock type, but sheep and goats are also important for many smallholder farmers. Throughout the region, substantial areas are owned by commercial farmers cultivating crops, though there is also a large number of small-scale producers trying to meet their subsistence needs, while also contributing produce for the global market. For example, these small-scale producers provide fruits from Zimbabwe, and tobacco and tea from Malawi (Msangi, 2007). In Mozambique, up to 95 percent of the total agricultural land is used by small-scale farmers who depend on rainfed agriculture, and in Angola up to 90 percent of the farming population are smallholders.

The region is characterised by high population growth rates, low per capita income, high poverty, different land tenure systems, and large gender inequality (Timberlake and Chidumayo, 2011). For example, in Angola only 38 percent of households are headed by women.[10] Likewise, women are also disproportionately represented in both decision-making regarding natural resources management and in high levels of governance, as shown in the United Republic of Tanzania where women's involvement in forestry is weak,[11] while in Angola only 30 percent of members of parliament are women.[12] Furthermore, in Angola only 53 percent of women are literate, compared to 80 percent among men.[13] In the whole region, food security is low, and all countries that are covered by "presumed drylands" have been classified as displaying acute food insecurity by the IPC.[14] This analysis includes some worrying trends, such as a rise in the prevalence of stunting in children under five years old from 29.2 percent to 37.6 percent between 2012 and 2017 in Angola (FAO et al., 2018).

The Miombo–Mopane woodlands provide numerous ecosystem services for local communities such as energy, food (mushrooms, honey, fruits, insects, among others) and medicines (Timberlake and Chidumayo, 2011; Syampungani *et al.*, 2009). Wood remains the main source of energy for cooking, and wild foods contribute significantly to the region's food security (Chepstow-Lusty *et al.*, 2006; Gumbo *et al.*, 2018). In particular, many indigenous species of fruit trees play a crucial nutritional role, including *Sclerocarya birrea*, *Uapaca kirkiana*, *Parinari curatellifolia* and *Azanza garckeana*. Furthermore, species from genera such as *Julbernardia, Isoberlinia, Syzygium* and *Brachystegia* provide important nectar sources for beekeeping (Ribeiro, Snook and Nunes de Carvalho Vaz, 2019). Some forest products such as indigenous fruits or edible caterpillars increasingly add to local incomes (Chidumayo and Mbata, 2002; Akinnifesi *et al.*, 2006); notably, the mopane worm (*Imbrasia belina*) is economically very important across southern Africa (Makhado *et al.*, 2014). It is estimated that both wood and non-wood products contribute to the livelihoods of 100 million rural and 50 million urban people in the region. For example, in the United Republic of Tanzania, the forestry, agriculture and fisheries sectors represented 30 percent of the GDP in 2017

[8] https://www.worldbank.org/en/country/malawi/overview; https://www.worldbank.org/en/country/burundi/overview

[9] MINAGRIF (2017). Angola's Medium-Term Development Plan for the Agrarian Sector (PMPSA), 2018–22.

[10] INE (2014). Population Census. Data on heads of household male/female ratio are only published for the nationally aggregated tier.

[11] National Strategy for Mainstreaming Gender in Climate Change for the United Republic of Tanzania, 2013.

[12] AfDB (2008). Angola – Country Gender Profile. African Development Bank/Fund; World Bank Group, 2019, Angola: Systematic Country Diagnostic Creating Assets for The Poor. http://documents.worldbank.org/curated/en/337691552357946557/pdf/angola-scd-03072019-636877656084587895.pdf

[13] CEDAW. Committee on the Elimination of Discrimination against Women considers Angola's report, January 2019. https://www.ohchr.org/en/NewsEvents/Pages/DisplayNews.aspx?NewsID=24225&LangID=E

[14] http://www.ipcinfo.org/ipc-country-analysis/

(World Bank, 2019).

Woodlands provide over two thirds of all energy used in the Miombo–Mopane woodland area. In Angola, Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe, biomass accounts for 60 to 90 percent of energy consumption (Gumbo *et al.*, 2018). In rural areas, it is mostly firewood that is used for fuel, while inhabitants of urban areas use traded products such as charcoal, which is one of main reasons for deforestation (Lisboa *et al.*, 2020). Production of charcoal provides employment to many people in rural areas (Jones, Ryan and Fisher, 2016; Smith, Hudson and Schreckenberg, 2017). For example, the charcoal sector in the United Republic of Tanzania has an estimated value of USD 650 million (FAO, 2017), while in Malawi charcoal production contributes to around 0.5 percent of GDP (Kambewa *et al.*, 2007).

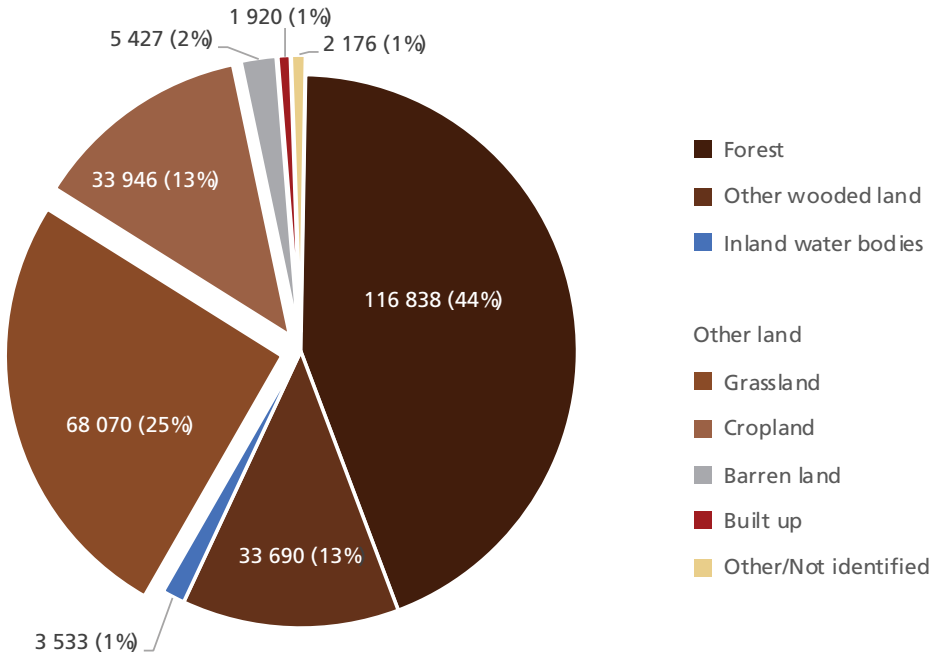
3.2.2 Land use and vegetation in "presumed drylands" of Miombo–Mopane woodlands

In Miombo–Mopane woodlands, "presumed drylands" comprise 265.6 million hectares (Figure 21). Forests cover 44 percent of the "presumed drylands" area of the Miombo–Mopane woodlands, while grasslands cover 25 percent, cropland 13 percent and other wooded land 13 percent (Figure 24). The remaining land is classified as barren land (around 2 percent), while built-up areas and inland water bodies cover around 1 percent each of the region's "presumed drylands".

More than half (55 percent) of "presumed dryland" forests in the Miombo–Mopane woodland area are natural broadleaved forests, followed by mixed broadleaved and coniferous forests (21 percent), coniferous forests (5 percent), and riparian and gallery forests (4 percent). Fifteen percent of the forest was recorded as other or not identified. The forests are mainly dominated by trees from the legume subfamily Caesalpinioideae, such as species in the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia* (Timberlake and Chidumayo, 2011; Williams *et al.*, 2008).

Crops are mostly grown on non-irrigated cropland (94 percent), and there is only 5 percent of irrigated cropland and 1 percent with perennial crops. Inland water bodies mostly consist of permanent lakes and pools (48 percent) and permanent rivers or inner deltas (24 percent), while 12 percent is covered by marshes on inorganic soils and 7 percent are seasonal rivers, with the remaining

FIGURE 24. Distribution of land uses in "presumed drylands" ('000 ha) in the Miombo Mopane



9 percent comprising coastal delta, seasonal lakes, among others (Annex 3). The vegetation cover in other wooded land is mainly dominated by shrubland (62 percent), followed by grassland with trees and shrubs (19 percent) and grasslands with shrubs (10 percent). The assessment did not identify the vegetation cover type for 9 percent of other wooded land.

The assessment shows that 56 percent of presumed dryland forest has a dense canopy cover

FIGURE 25. Tree canopy cover in forest and other wooded land in "presumed drylands" in Miombo–Mopane

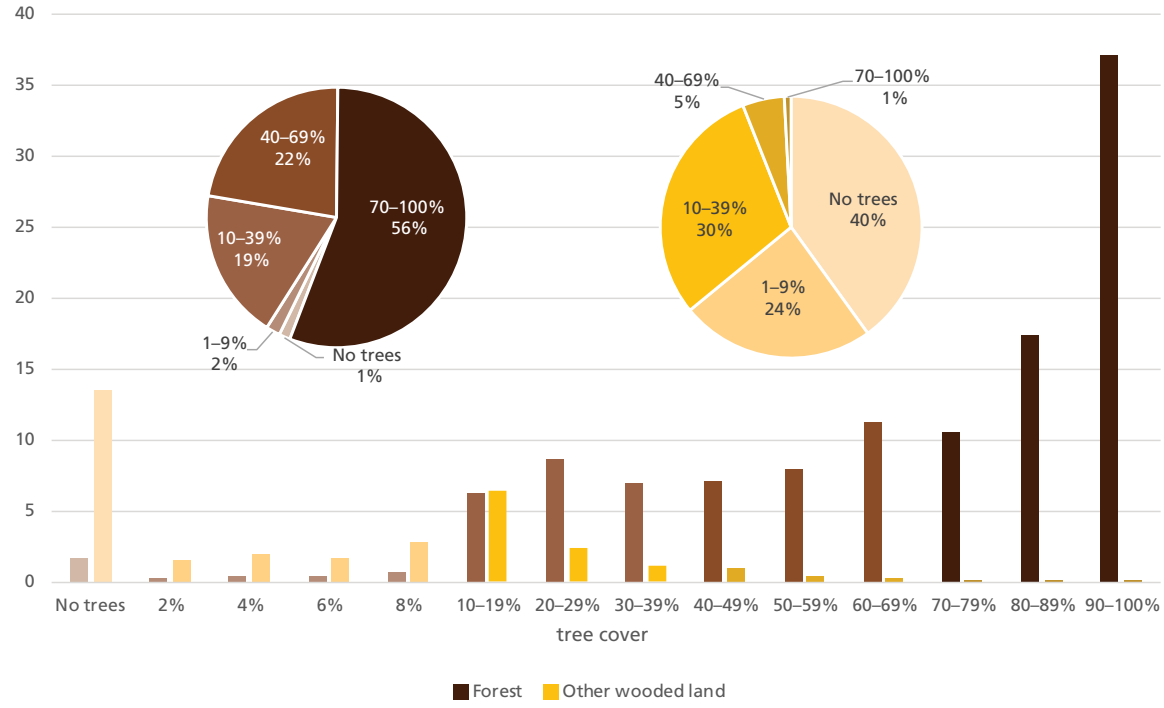
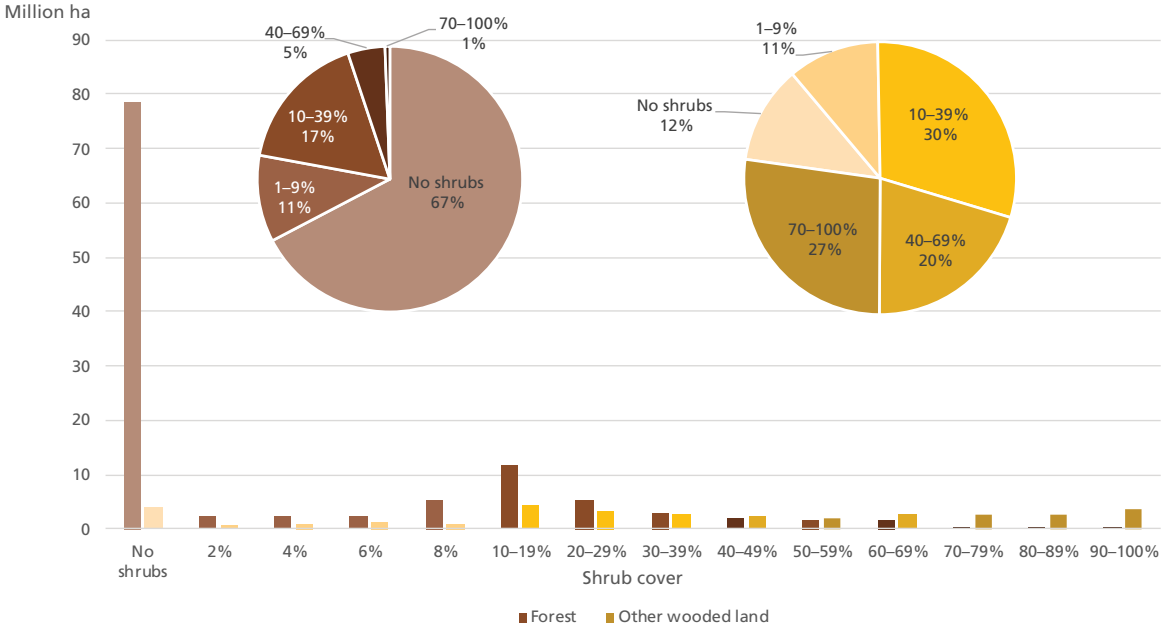
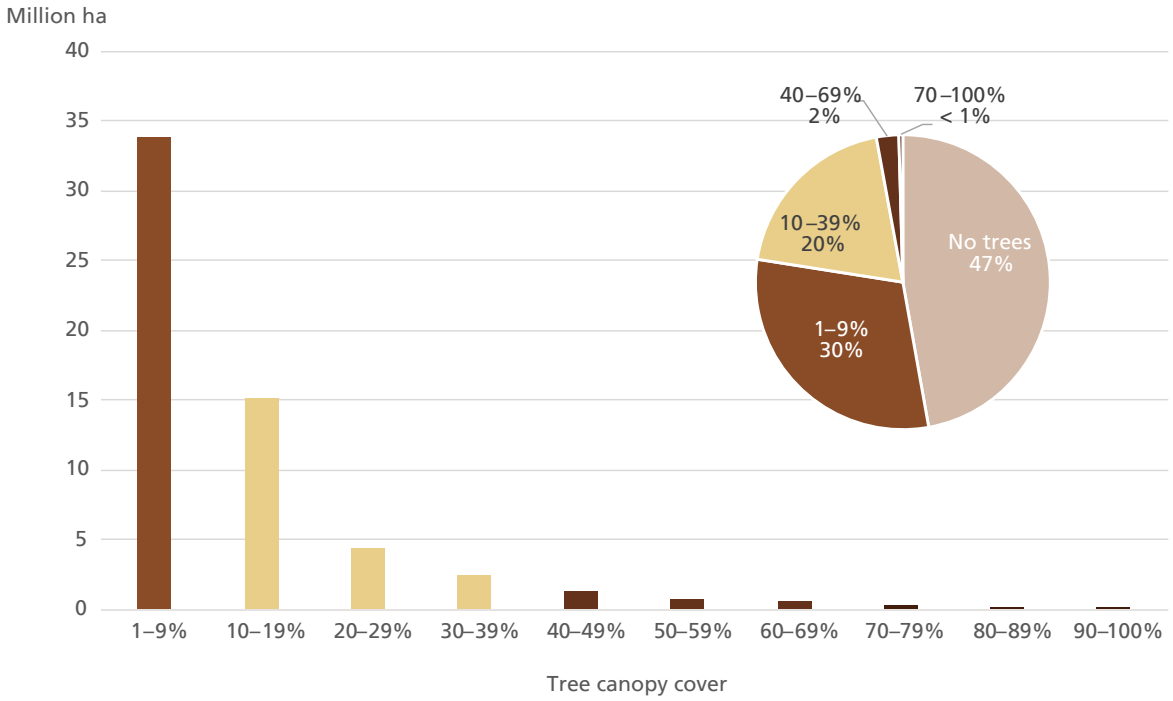


FIGURE 26. Shrub cover in forest and other wooded land in "presumed drylands" in Miombo–Mopane



of 70 to 100 percent, and only 2 percent of the forest has a canopy cover in the lowest range of 1 to 9 percent. As much as 40 percent of other wooded land has no tree cover, while 30 percent has canopy cover between 10 and 39 percent (Figure 25). Shrubs are present only on 34 percent of the forest area while they are more common on other wooded land (Figure 26). Trees are present on 53 percent of the land outside forest, with canopy cover of 10 to 39 percent on 20 percent of the area and canopy cover of 1 to 9 percent on 30 percent of the area (Figure 27).

FIGURE 27. Trees canopy cover in other land in "presumed drylands" in Miombo–Mopane woodland



3.2.3 Land change in Miombo–Mopane woodlands

3.2.3.1 Human impacts and drivers of degradation

Over the last three decades, the growing population and unsustainable land use practices in the Miombo–Mopane woodland region have led to increased deforestation and land degradation. Although there are no reliable data on the area of forest lost in the whole Miombo–Mopane woodland or in the area covered by the "presumed drylands", it was estimated that over 38 million hectares of forest were lost in Angola, the Democratic Republic of the Congo, Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe between 1990 and 2005 (FAO, 2015; Gumbo *et al.*, 2018). The key causes of negative impacts are unsustainable farming practices and overgrazing, firewood gathering and production of charcoal (Chidumayo, 1991; Moura *et al.*, 2017). Recently, the emergence of urban markets for products such as charcoal, timber and tobacco have led to even more forest clearing and degradation (Gumbo *et al.*, 2018), and this is expected to grow in the future. For example, Iimaya *et al.* (2014) showed that in 2015, 1.6 million hectares were needed to meet the charcoal demand in sub-Saharan Africa and estimated that by 2050, as much as 4.4 million hectares will be needed annually. Forests are also removed to farm commercial commodities, such as palm oil and sugar cane. For example, final country reports of the LDN Target Setting Programme for Malawi,[15] the United Republic of Tanzania[16] and Zambia[17] indicated a decline in forest areas and an increase in agricultural areas. Similarly, Green *et al.* (2013) have shown that the Eastern Arc Mountains of the United Republic of Tanzania have lost 43 percent of miombo woodland between 1975 and 2000 and predict that by 2025, an additional 42 percent will be lost.

Weather conditions and climate change contribute greatly to land degradation. Recurring droughts with high temperatures, high winds and low relative humidity increase the risk of erosion (Matari, 2007). Anthropogenic fires, exacerbated by climate change, are a major ecological disturbance in the Miombo–Mopane woodlands. In the United Republic of Tanzania, for instance, they impact up to 50 percent of the woodland area each year (Tarimo *et al.*, 2015).

[15] https://knowledge.unccd.int/sites/default/files/ldn_targets/Malawi%20LDN%20TSP%20Country%20Report.pdf
[16] https://knowledge.unccd.int/home/country-information/countries-having-set-voluntary-ldn-targets/tanzania-united-republic
[17] https://knowledge.unccd.int/search?text=Zambia&f%5B0%5D=type%3Aunccd_content

3.2.3.2 Consequences of land degradation

The growing population and its need for agricultural land, leading to overharvesting and overgrazing, together with climate change impacts drive deforestation and land degradation in the region. Clearing vegetation for agriculture and the concomitant loss of woodland cover, as well as infrastructural developments and resulting fragmentation, negatively impact the region's hydrology and ecological functions, with cascading effects on biodiversity (Timberlake and Chidumayo, 2011). Moreover, the harvesting of biomass, for instance, for fuelwood, affects soil carbon storage (James and Harrison, 2016), while charcoal production results in changes in the soil chemistry (Sedano *et al.*, 2016), thus affecting the functioning and composition of soil microbial communities (Lisboa *et al.*, 2020). While there are no data that show the extent of degradation in the whole Miombo–Mopane woodland area, Tamene *et al.* (2019) have clearly indicated that soil structure degradation, nutrient limitations and low soil organic carbon (SOC) concentrations are widespread across southern Africa. As such, this jeopardises the livelihoods of millions of people dependant on different woodland products and ecosystem services (Gumbo *et al.*, 2018). Over 80 percent of rural and urban dwellers in the region strongly depend on these resources and the safety net they provide. For example, during poor crop years, wild foods can contribute to over 30 percent of the local people's diets (Gumbo *et al.*, 2018). The overexploitation of non-timber forest products (NTFPs) also has negative consequences by contributing to degradation. For example, honey gathering in the United Republic of Tanzania using traditional beehives, made by debarking and felling trees, is highly destructive (Ribeiro, Snook and Nunes de Carvalho Vaz, 2019), while harvesting of other NTFPs is usually unsustainable, leading, among other impacts, to the disappearance of medicinal plants (UNIQUE, 2020).

Land use change in the Miombo–Mopane woodlands specifically impacts women, as they are mainly responsible for the harvesting and processing of woodland products. For example, women in the United Republic of Tanzania largely use fuelwood rather than charcoal for energy due to the high cost of charcoal, their limited income, as well as competition for and constraints on land and tree ownership (Preston, Pypker and Orr, 2017; Chepstow-Lusty *et al.*, 2006). At the same time, men more commonly gain from the ongoing commercialization, as they often work in the production of commercial products such as timber, charcoal and honey (Kalaba, Quinn and Dougill, 2013). In a study from the United Republic of Tanzania, it was found that men produce charcoal for sale at markets, while almost no charcoal was used locally (Preston, Pypker and Orr, 2017). Hence, the degradation of the Miombo–Mopane woodlands will exacerbate poverty, particularly among the most vulnerable groups, such as the elderly, children and women (Gumbo *et al.*, 2018).

Ongoing climate change is both a consequence of land degradation and contributes to further degradation. The higher temperatures and more extreme dry and wet seasons associated with climate change likewise influence existing disturbances, such as fire regimes and shifting cultivation patterns, in turn leading to biodiversity declines and a decrease in food security (Chidumayo, 2005; IPCC, 2014). While predictions of rainfall patterns across the Miombo–Mopane woodlands are uncertain, there is medium confidence that this area will experience a reduction in precipitation by the end of the century, and high confidence that temperatures will generally increase, leading to water stress (Sutcliffe, Dougill and Quinn, 2016). Regional assessments of climate vulnerability show that most of the countries of the Miombo–Mopane woodlands face high climate risk and accompanying food insecurity (Sutcliffe, Dougill and Quinn, 2016). Climate change will have direct significant negative impacts on local communities' livelihoods and natural resources. For example, climate change-related losses in agricultural GDP in the United Republic of Tanzania were estimated at USD 27 billion over the next 50 years, i.e. representing annual losses of around USD 540 million (the United Republic of Tanzania, 2019).

3.2.4 Opportunities and best practices contributing to land degradation neutrality

Numerous approaches have been applied in the Miombo–Mopane woodlands to tackle the ongoing land degradation challenges. The application of sustainable agrosilvopastoral systems, sustainable land management initiatives and better fire management policies have the potential to contribute to land degradation neutrality. In addition, local communities can apply different adaptive strategies in order to maintain their livelihoods in the face of climate change and ongoing land degradation.

3.2.4.1 Sustainable agrosilvopastoral systems

Agroforestry systems

Agroforestry systems, particularly silvopastoral systems, are important approaches to land use in the Miombo–Mopane woodland area (Box 5). While there are no data that show the scale of adoption of agroforestry systems in this region, different types are probably quite widespread. For example, Ajayi *et al.* (2011) highlight the Zambezi Basin Agroforestry Programme,[18] in which as many as around 400 000 smallholder farmers adopted fertilizer trees (i.e. trees used in agroforestry systems to improve conditions of soil use for farming) in Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe. They also emphasise the example from Zambia, where the average size of plots with fertilizer trees expanded from 0.07 to 0.2 hectares between the mid-1990s and 2003, translating into over 13 000 hectares of such systems at that time in Zambia alone.

Agroforestry systems are often seen as an important component of climate-smart agriculture (CSA), as they not only lead to enhanced agricultural productivity and an increase in food security by delivering additional food resources (Musa *et al.*, 2018), but also sequester carbon and help adapt agriculture to climate change (Amadu, Miller and McNamara, 2020; Kwesiga *et al.*, 2003). The use of supplementary fodder trees increases weight gains and milk production of dairy cattle (Toth *et al.*, 2017), while fertilizer trees in cropping systems improve soil fertility and structure, as well as residue retention, all leading to increased productivity (Garrity *et al.*, 2010; Thierfelder *et al.*, 2018). For example, the use of fertilizer trees such as the native legume *Faidherbia albida* in crop fields, as part of conservation agriculture efforts in Zambia promoted by the Zambian Conservation Farming Unit (CFU) since 1996, has led to increases in maize yields of between 6 and 200 percent, depending on the conditions and practices used (Garrity *et al.*, 2010). CFU trains 200 000 farmers each year in adopting CA practices, and nearly 50 percent of them are women.[19] Another example comes from Malawi, where agroforestry practices were promoted by the Agroforestry Food Security

Box 5
Conditions for successful adoption of agroforestry systems

- Adoption and upscaling of agroforestry practices require consideration of complex social, economic and environmental dimensions.
- Besides availability of technical options, active encouragement of farmers is necessary for them to adopt innovations, while partnerships are required between multiple institutions.
- General lack of technical knowledge can be a large constraint to adopting agroforestry practices.
- Level of education, gender disparities, land tenure security, lack of market access, and exposure to extension services are important factors determining adoption of agroforestry systems.
- Size of land holdings may determine types of technologies adopted.
- Local armed conflicts can also constrain adoption of agroforestry systems.

Sources: Source: Msangi, J.P. 2007. Land degradation management in Southern Africa. In M.V.K. Sivakumar & N. Ndiangui, eds. Climate and Land Degradation. pp. 488–499; Quinion, A. et al. 2010. Do agroforestry technologies improve the livelihoods of the resource poor farmers? Evidence from Kasungu and Machinga districts of Malawi. Agroforestry Systems, 80(3): 457–465; Ajayi, O.C. et al. 2011. Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). International Journal of Agricultural Sustainability, 9(1): 129–136; Delgado-Matas, C. et al. 2015. Land use evolution and management under recurrent conflict conditions: Umbundu agroforestry system in the Angolan Highlands. Land Use Policy, 42: 460–470; Kakhobwe, C.M. et al. 2016. Scaling up agroforestry farming systems: lessons from the Malawi Agroforestry Extension Project. Journal of Agricultural Extension, 20(1): 153–162; Toth, G.G. et al. 2017. Constraints to the adoption of fodder tree technology in Malawi. Sustainability Science, 12(5): 641–656; Musa, F.B. et al. 2018. Adoption and the role of fertilizer trees and shrubs as a Climate Smart Agriculture practice: The case of Salima District in Malawi. Environments, 5(11).

[18] https://www.worldagroforestry.org/publication/zambezi-basin-agroforestry-programme-icraf-zimbabwe-agroforestry-project

[19] http://conservationagriculture.org/

Programme (AFSP), initiated by the World Agroforestry Centre (ICRAF), which reached a total of 184 463 households between 2007 and 2011.[20] In this case, intercropping maize with the non-native leguminous tree *Gliricidia sepium* led to an increase in maize yields from around 1 to an average of 3.7 tonnes/hectare (Garrity *et al.*, 2010), thus strengthening the food security and nutrition of the households involved. In a further CSA programme, funded by the US Agency for International Development (USAID) between 2009 and 2014 in Malawi, an average increase in maize yields of 20 percent was achieved by smallholder farmers, and utilising fertilizer trees was identified as the most important component of the programme (Amadu, Miller and McNamara, 2020).

Agroforestry systems may also contribute to increased incomes for local communities. For example, a recent study from Malawi has shown that the use of fertilizer trees by smallholder farmers increased the value of food crops by 35 percent and that the increase was particularly important for small landholders, with farms up to 2 acres (0.81 hectares) (Coulibaly *et al.*, 2017). Another study from Malawi revealed that the use of fertiliser tree technologies, besides increasing crop production, also contributed additional income to local people through the sale of fuelwood and seeds (Quinion *et al.*, 2010). Although, the testing of fertilizer trees was shown to be more likely by wealthier farmers, it was poorer farmers who continued more with this approach, as they could not purchase fertilizers and their livelihoods depended on maintaining production (Ajayi *et al.*, 2011). Agroforestry has also been suggested as a good way to contribute wood fuel sustainably for charcoal production as that would help reduce wood harvesting in the forests. However, it was recommended that a systematic approach is required that takes into account the needs of local farming systems if such approaches are to be introduced successfully (Iiyama *et al.*, 2014).

Besides purposeful establishment of agroforestry systems, natural regeneration after abandonment of specific land uses is another option for reversing land degradation. As such, woodlands in the Miombo–Mopane area have a high regenerative capacity. Natural regeneration tends to occur rapidly, usually just a few years after tree harvesting or cropland abandonment (Williams *et al.*, 2008; Gumbo *et al.*, 2018). It has been shown in a study from Mozambique that allowing natural regeneration after abandonment of *machambas* (cultivated land) leads to an annual increase in soil carbon stocks by 0.7 tonnes/hectare and a rise in biodiversity (Williams *et al.*, 2008).

3.2.4.2 Sustainable land management

Different types of sustainable land management (SLM) practices, such as conservation agriculture (CA), have been applied in the agricultural areas of the Miombo–Mopane woodlands region, showing some positive effects. For example, in grasslands, reseeding with nitrogen-fixing trees or herbaceous fodder legumes and controlled grazing were shown to speed up the build-up of soil organic matter (Tamene *et al.*, 2019). In a study in Zimbabwe, CA with crop rotation, crop residue retention and minimum soil disturbance resulted in improved moisture use efficiency and a rise in productivity and yields (Marongwe *et al.*, 2011). CA also improves soil structure and carbon content, thus mitigating land degradation and climate change effects (Thierfelder and Wall, 2010; Marongwe *et al.*, 2011). However, the area under conservation agriculture remains relatively low, limiting the potential of this approach for ensuring household food security and delivering impacts at national level (Marongwe *et al.*, 2011). Limitations in labour, for instance, for soil preparation and weeding have likewise been acknowledged and more mechanized conservation agriculture systems will be necessary for upscaling (Marongwe *et al.*, 2011).

Another SLM practice suggested for some areas of the Miombo–Mopane woodlands region is employing rainwater harvesting systems, in which a catchment subsystem receives rainwater and generates run-off, while a farming subsystem receives and stores both rainfall and run-off to meet watering requirements (Gowing *et al.*, 2003). Experiments conducted in the United Republic of Tanzania show that such systems have the potential to increase productivity of maize cropping systems (Gowing *et al.*, 2003). Other SLM approaches used in the Miombo–Mopane woodlands area include the rehabilitation of rangelands by reintroducing key pasture and fodder species into strategic areas through stakeholder participation, the application of communal management plans,[21] and the

[20] https://www.oaklandinstitute.org/sites/oaklandinstitute.org/files/Food_Security_Malawi.pdf
[21] https://qcat.wocat.net/ar/wocat/technologies/view/technologies_3141/

restoration of traditional pastoral management forums.[22] The latter approach has for instance been implemented in a project called "Land rehabilitation and rangelands management in smallholder agropastoral production systems in south-western Angola",[23] and resulted in empowering local land users and improving participation, thus helping them to implement SLM practices.

3.2.4.3 Fire management

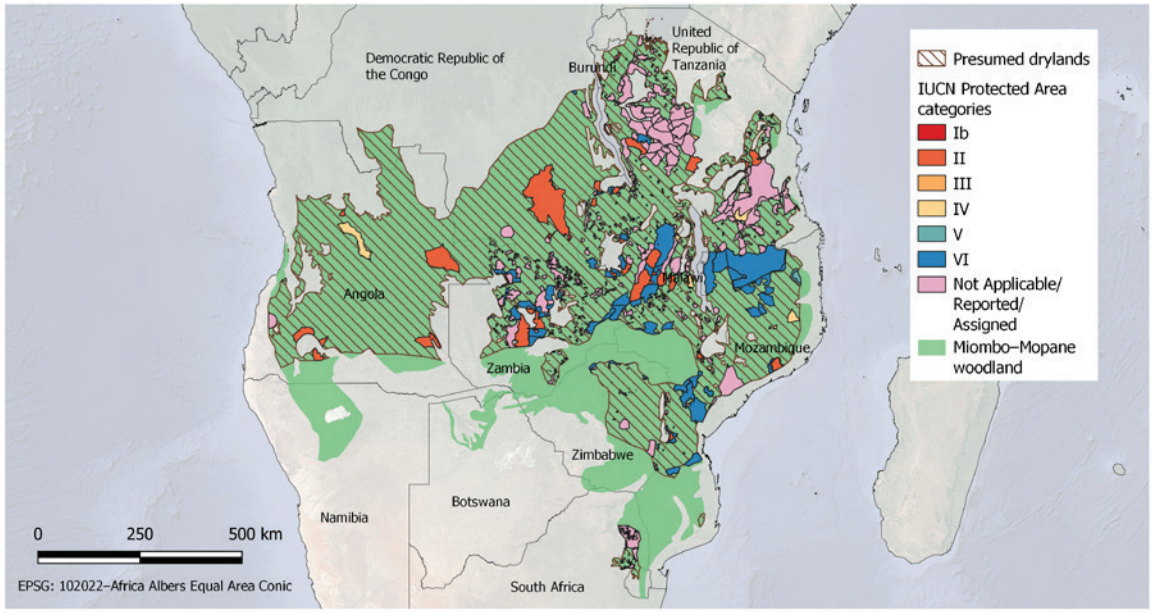
One of the strategies to slow down soil degradation is appropriate fire management. Traditional fire management, instead of suppressing fires and controlling their frequency, consists of manipulating the intensity of fires by setting small patchy fires early in the growing season in order to create natural fire breaks in the landscape, thus mitigating large destructive fires later in the dry season (Ryan and Williams, 2011). Based on a long-term fire management experiment in Zimbabwe, Ryan and Williams (2011) suggest that such traditional approaches to mitigating fire intensity are more practicable than fire suppression. However, as in the Cerrado, controversies remain concerning the use of fire in traditional management of the Miombo–Mopane woodlands region (Tamene *et al.*, 2019).

Some countries in the Miombo–Mopane region currently participate in the Monitoring for Environment and Security in Africa (MESA) programme[24] in order to identify and monitor natural and anthropogenic forest fires, reduce their impact and to help in risk and disaster planning.

3.2.4.4 Restoration, conservation and land degradation management

All the countries within this region have a vast number of protected areas with various conservation designations, ranging from national parks, game management areas, Ramsar sites, national reserves, forest reserves, game reserves, among others. Of all the countries with Miombo–Mopane woodlands, Angola has the smallest number of protected areas in the World Database on Protected Areas (WDPA). Protected areas in the region, according to IUCN categories and areas of international importance, are shown in Figure 28. The total area of protected areas, both at national and international levels such as Ramsar sites and biosphere reserves, comprise approximately 23 percent of "presumed drylands" of the Miombo–Mopane woodland area. When only IUCN categories of protected areas are taken into account, this area is slightly below 15 percent.

Figure 28: Protected areas and "presumed drylands" in the Miombo–Mopane woodlands according to the IUCN classification



Source: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001; IUCN and UNEP-WCMC, 2021

[22] https://qcat.wocat.net/ar/wocat/approaches/view/approaches_3173/
[23] https://qcat.wocat.net/ar/wocat/approaches/view/approaches_3173/
[24] http://moi.govmu.org/mesa/pages/mesa.php

Different projects and initiatives are being implemented in the Miombo–Mopane woodland region that aim to tackle land degradation and improve local livelihoods. These are usually funded by external actors, such as the World Bank, UNEP or large international NGOs. Examples of such initiatives include the Shire Natural Ecosystems Management Project[25] and Enhancing the Resilience of Agro-Ecological Systems Project[26] in Malawi. The Shire project aimed at developing a planning framework to improve land and water management for ecosystem and livelihood benefits, and demonstrated innovative approaches for integrated catchment management. One of the key lessons learnt was that reversing watershed degradation requires significant investment in strengthening capacity at all levels, particularly in institutions, intersectorial coordination and land use planning, as well as information and infrastructure, and thus long-term financial resources. Furthermore, the capacity of implementing agencies needs to be considered and strong government commitment is required. The Enhancing the Resilience of Agro-Ecological Systems Project focused on food security and sustainable management of important ecosystem services. It facilitated reforestation and natural regeneration of large areas, supported SLM practices for riverbank protection, and trained farmers in SLM application, as well as providing support for establishing businesses based on non-wood forest products, such as honey. Another project in Malawi, the Agroforestry Food Security Programme,[27] promoted agroforestry practices by training farmers and providing them with agroforestry materials (e.g. seeds and seedlings), as well as organisation of roadside demonstrations and distribution of necessary information. Malawi has also hosted the biodiversity conservation initiative Protecting Ecosystems and Restoring Forests in Malawi (PERFORM),[28] which aimed at improving climate resilience of the country and enhancing sustainable forest management.

Other notable initiatives have been carried out. In Zimbabwe, Support to Alignment of Zimbabwe's National Action Programme and Reporting Process to the UNCCD 10-Year Strategy[29] was implemented to help the country meet its obligation to the UNCCD Convention. An ongoing project in Angola (2016–2022), Promotion of Sustainable Charcoal in Angola through a Value Chain Approach,[30] aims at introducing energy-efficient charcoal technologies and facilitating the market for sustainable charcoal. In Mozambique, the Mozambique Conservation Areas for Biodiversity and Development Project[31] included one of the areas covered by the "presumed drylands", namely the Chimanimani landscape. Between 2015 and 2018, the project enhanced biodiversity in over 1.8 million hectares of conservation areas, benefited more than 38 000 people and led to the creation of an additional 1 666 jobs in tourism in conservation areas. Furthermore, a recent project that is currently (2017–2022) being implemented in the country – the Mozambique Forest Investment Project,[32] includes two provinces that contain some areas of "presumed drylands" (Cabo Delgado and Zambezia) and aims at improving forest and land management in these areas. Until 2020, SLM practices in over 11 000 hectares were adopted by around 2 800 land users, around 750 hectares of forests were planted, and almost 3 000 hectares of agroforestry systems were established.

3.2.4.5 Adaptive livelihood strategies

Local communities adapt to harsh environmental conditions by changing their land use and management strategies. In Zimbabwe, for instance, conservation agriculture (see previous section) was adopted in response to severe droughts (Masunungure and Shackleton, 2018). Importantly, farmers in Zimbabwe apply local knowledge to manage water scarcity and ensure crop production by local innovations such as using rain corridors, i.e. in areas likely to get more rain, or cultivating in sandy rivers in order to utilise the moisture and nutrients washed down by seasonal rivers during previous rainfall events (Maleksaeidi and Karami, 2013). Hence, local knowledge is commonly used to adapt to unfavourable environmental changes in the Miombo–Mopane woodland region.

[25] https://www.thegef.org/project/shire-natural-ecosystems-management-project
[26] https://www.thegef.org/project/food-iap-enhancing-resilience-agro-ecological-systems-erasp
[27] http://www.worldagroforestry.org/project/agroforestry-food-security-programme-afsp-ii; http://www.worldagroforestry.org/news/agroforestry-food-security-programme-afsp-malawi
[28] https://www.tetratech.com/en/projects/protecting-ecosystems-and-restoring-forests-in-malawi
[29] https://www.thegef.org/project/support-alignment-zimbabwes-national-action-programme-and-reporting-process-unccd-ten-year
[30] https://www.thegef.org/project/promotion-sustainable-charcoal-angola-through-value-chain-approach
[31] https://projects.worldbank.org/en/projects-operations/project-detail/P131965?lang=en
[32] https://projects.worldbank.org/en/projects-operations/project-detail/P160033?lang=en

A further example is highlighted by the home-grown school feeding (HGSF) programmes (FAO and WFP, 2018), which are designed to stimulate local food production. Such programmes create a stable demand for quality and safe food, support the development of local skills and improve food security by purchasing food from local smallholder farmers and processors.

In addition, numerous adaptation strategies are being applied at the household level. For example, in Zimbabwe, as a response to climate change, including droughts, many local people have sought to diversify their income activities, by selling woodland products such as wild fruits, thatch grass and firewood, undertaking casual labour, or migrating in search of work. These household-level strategies are often only short-term coping mechanisms, and some may even have negative environmental impacts, such as selling baobab fibre for weaving that may affect baobab tree health, a keystone species in arid environments, with multiple uses (Masunungure and Shackleton, 2018).[33]

3.3 "PRESUMED DRYLANDS" ON THE QINGHAI–TIBETAN PLATEAU

Key messages

- "Presumed drylands" on the Qinghai–Tibetan Plateau (QTP) cover 152.87 million hectares.
- Sixty-seven percent of the QTP area is barren land and 24 percent is covered by grasslands. Forests and inland water bodies cover 4 percent each, while other wooded land comprises about 1 percent of the area, with cropland less than 1 percent.
- Slightly more than half (54 percent) of cropland is irrigated cropland, while 43 percent comprises non-irrigated cropland and 4 percent is for perennial crops.
- The QTP is an exceptional biodiversity hotspot globally, hosting over 12 000 plant species, 5 000 epiphyte species, 532 bird species and 210 mammalian species. However, there are relatively few protected areas on the QTP.
- There are about 65 million livestock on the QTP that supply benefits such as meat, wool, milk and fuel and constitute an important component of national economic growth and food security, providing livelihoods to almost 10 million people. The grasslands in the region also provide important ecosystem services, such as carbon storage, water and soil retention, and maintain biodiversity.
- Over the second half of the twentieth century, improved infrastructure and increased market demand for meat led to a rise in livestock production, resulting in the growth of both livestock and human populations. Simultaneously, the region experienced changes from traditional mobile pastoralism towards more sedentary pastoralism. These trends have caused overgrazing that, together with development of infrastructure, urbanisation and tourism activities, currently contribute to land degradation on the QTP.
- Many policies and initiatives focus on decreasing grazing pressure on the grasslands, such as sedentarising herders or imposing grazing bans. Such approaches are often controversial and need to be balanced by a holistic grazing management approach that builds on traditional knowledge and mobility of herders, while promoting inclusive, participatory dialogue with local communities. If needed, possibilities for alternative livelihoods or payments for ecosystem services (PES) should be provided. Temporal fencing, grazing bans or grazing rotation, planned together with the local communities in a participatory process, are recommended in highly degraded areas in order to allow for their recovery.
- Restoration and rehabilitation are key approaches for restoring areas already degraded on the QTP. These approaches usually aim at temporarily decreasing grazing in such highly degraded areas, and thus allowing the revegetation of degraded grasslands.

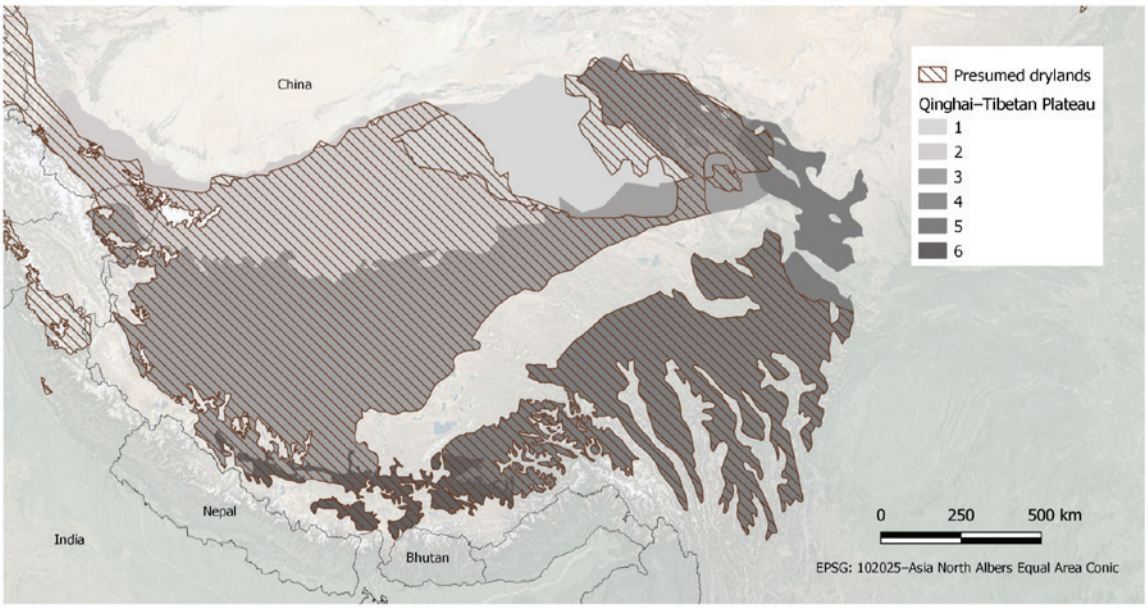
3.3.1 The Qinghai–Tibetan Plateau: general information, biodiversity and ecosystem services

The Qinghai–Tibetan Plateau (QTP) lies in the southwest of China and covers around 25 percent of the country's entire territory, or 2.5 million square kilometres. It includes the whole Tibet Autonomous Region and Qinghai Province, along with parts of Gansu, Sichuan and Yunnan Provinces (Fayiah *et al.*, 2020). It is the highest plateau in the world, with an average elevation of

[33] https://theconversation.com/baobab-trees-have-more-than-300-uses-but-theyre-dying-in-africa-98214

around 4 000 metres above sea level (Wen *et al.*, 2014), and thus commonly called "the roof of the world" (Baiping *et al.*, 2002). Six different ecoregions are part of the QTP: Qaidam Basin semi-desert, North Tibetan Plateau–Kunlun Mountains alpine desert, Central Tibetan Plateau alpine steppe, Qilian Mountains subalpine meadows, Southeast Tibet shrublands and meadows, and the Yarlung Tsangpo arid steppe (Figure 28).

FIGURE 29 Coverage of "presumed drylands" on the Qinghai–Tibetan Plateau (the numbers indicate the following ecoregions: 1. Qaidam Basin semi-desert; 2. North Tibetan Plateau–Kunlun Mountains alpine desert; 3. Central Tibetan Plateau alpine steppe; 4. Qilian Mountains subalpine meadows; 5. Southeast Tibet shrublands and meadows; 6. Yarlung Tsangpo arid steppe)



Sources: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001

The average annual temperature on the QTP is 1.6 °C, with January temperatures ranging from 1 to 7 °C and July temperatures ranging from 7 to 15 °C. The average annual precipitation is slightly over 400 mm, most of which (60–90 percent) takes place between June and September, the wet, humid summer, while only around 10 percent of rainfall occurs between November and February, the arid winter (Xu, Gong and Li, 2008). Solar radiation is high (Liu *et al.*, 2012), but the plant growing season is short, only extending over 3.5 months (Leonard and Crawford, 2002), and there is low air pressure and CO_2 concentrations. Furthermore, soil profiles are very shallow, 30–50 cm deep, and poor in nutrients (Chang *et al.*, 2014; Li *et al.*, 2014).

The main vegetation type in the QTP is grassland, and there are seventeen different types of grasslands in the area, though eight of them only have minor coverage (below 1 percent). Alpine meadow, dominated by the endemic sedge species, *Kobresia pygmaea* and *Kobresia humilis*, covers the largest area of QTP grasslands (almost 45 percent), followed by alpine steppe (almost 29 percent) and alpine desert steppe (almost 7 percent) (Li, X.L. *et al.*, 2013a).

The QTP area is considered one of the 'Last Wilds' (Sanderson *et al.*, 2002) and it is part of China, a so-called 'megadiversity country' (Brooks *et al.*, 2006). It is an exceptional biodiversity hotspot globally, hosting over 12 000 plant species, 5 000 epiphyte species, 532 bird species and 210 mammalian species (Fayiah *et al.*, 2020), including four antelope species of ecological importance (Zhang *et al.*, 2021). The QTP also hosts a large variety of endemic and rare species and over 200 species important for medicine. Its unique location, biogeographic landscape, latitude and climate, as well as traditional system of mobile pastoralism makes it an important global ecological reservoir of alpine biodiversity (Fayiah *et al.*, 2020). It is furthermore considered one of the global centres of species formation and differentiation (Baiping *et al.*, 2002).

The rich biodiversity of the plateau is a source of numerous important ecosystem services, which support vital grazing lands for livestock, including yaks, sheep and goats (Harris, 2010; Liu *et al.*,

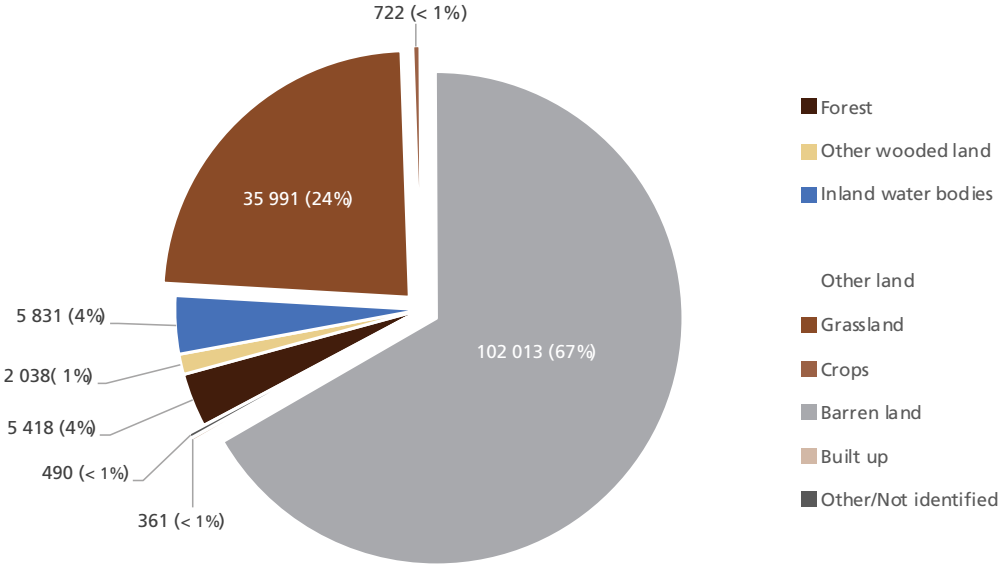
2018). Numbering about 65 million livestock in the QTP (Yang *et al.*, 2019), including nearly 41 million Tibetan sheep and 13 million yaks, these animals provide livelihoods to approximately 10 million people (Shang *et al.*, 2014). Herding is also an important part of the identity, culture and traditions of the local communities (Long *et al.*, 2008). Grazing livestock and healthy pastoral systems deliver many benefits, such as meat, wool, milk and fuel, thus covering essential domestic needs, and for many families, yak or sheep pasturing is the only source of subsistence. Large-scale livestock rearing is also a crucial component of national economic growth and food security. While there are no estimates of its contribution to national or regional gross domestic product (GDP), studies from other countries show that the contribution made by livestock can be relatively high. For example, pastoralists contribute 9.6 percent of GDP in Mongolia and 11 percent in Chad (FAO, 2020). Moreover, livestock rearing is seen by many Tibetans as cultural heritage and representing ways of life that should be preserved for future generations (Fayiah *et al.*, 2020). In addition to supplying local needs, the grasslands of the QTP are an important source of meat products for the Chinese market and provide herbal medicines and the medicinal caterpillar fungus (*Ophiocordyceps sinensis*), as well as having recreational and aesthetic values (He, 2018; Dong *et al.*, 2020b; Fayiah *et al.*, 2020).

The QTP grasslands also provide numerous regulating services, such as sandstorm prevention, and water and soil retention. Furthermore, the QTP area contributes to global climate regulation by sequestering large amounts of carbon, particularly in soils (Cao *et al.*, 2019; Wang *et al.*, 2002). Organic carbon is stored mostly in steppe and meadow soils and all together reaches 33.5 billion tonnes of carbon in the QTP, representing between 2.5 and 4 percent of the global soil-stored carbon pool, and over 23 percent of China's total soil-stored organic carbon (Liu *et al.*, 2018; Wang *et al.*, 2002). Lastly, the QTP is a source for a number of large rivers that provide water to around 1.5 billion people, thus playing a major role in water security in Asia (Li *et al.*, 2020). For example, the Three-Rivers Headwater Region in the QTP contains the headwaters of the three longest Asian rivers: Yangtze, Yellow River and Mekong (Shang *et al.*, 2014).

3.3.2 Land use and vegetation in "presumed drylands" of the Qinghai–Tibetan Plateau

In the Qinghai–Tibetan Plateau, "presumed drylands" cover 152.9 million hectares (Figure 29). The analysis revealed that as much as 67 percent of the QTP area is barren land, while 24 percent is covered by grasslands. Forests and inland water bodies cover 4 percent each, while other wooded land covers about 1 percent, and cropland represents less than 1 percent of the area (Figure 30).

FIGURE 30. Distribution of land uses in "presumed drylands" ('000 ha) of the Qinghai–Tibetan Plateau



The assessment shows that 50 percent of presumed dryland forest in the QTP has a dense canopy cover of 70–100 percent, followed by 32 percent with canopy cover of 40–69 percent, and 16 percent with canopy cover of 10–39 percent (Figure 31). At the same time, most other wooded

land (87 percent) is without canopy cover. There is very little shrub cover in the forest, while relatively much in other wooded land (Figure 32). There are almost no trees found outside forest in the QTP area (Figure 33).

FIGURE 31. Tree canopy cover in forest and other wooded land in "presumed drylands" of the Qinghai–Tibetan Plate

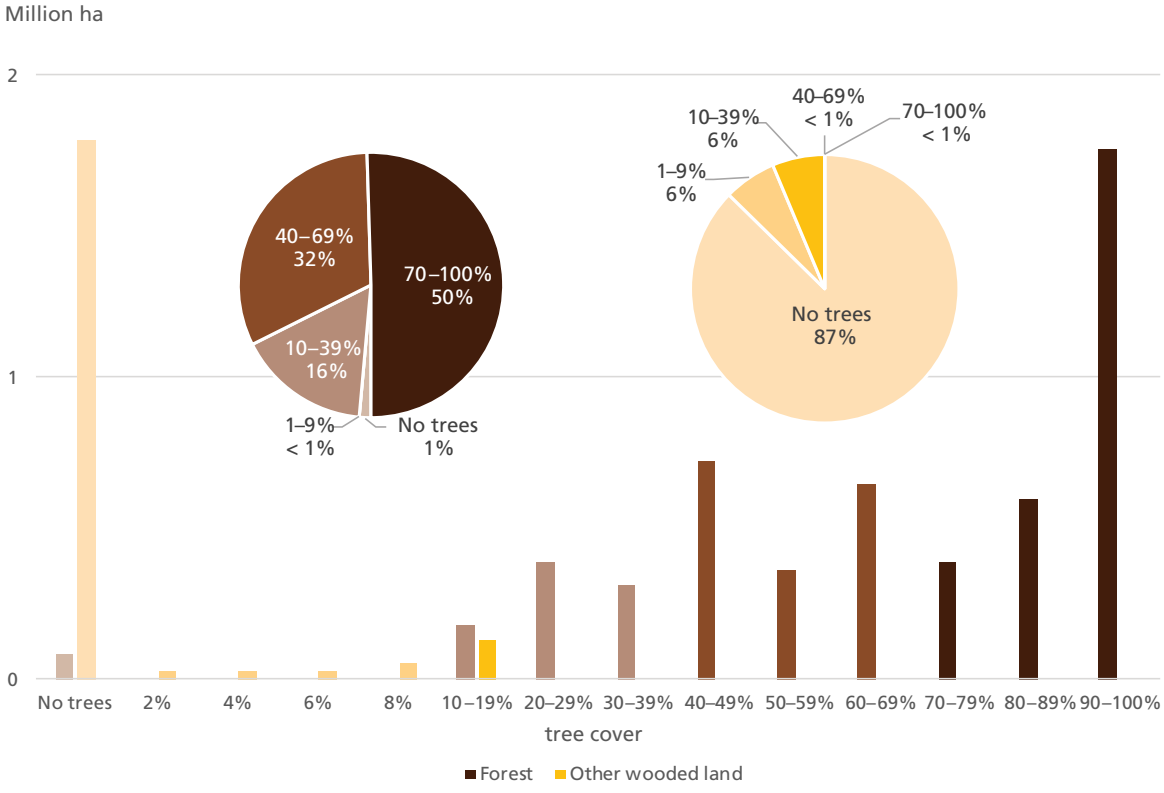


FIGURE 32. Shrub cover in forest and other wooded land in "presumed drylands" of the Qinghai–Tibetan Plate

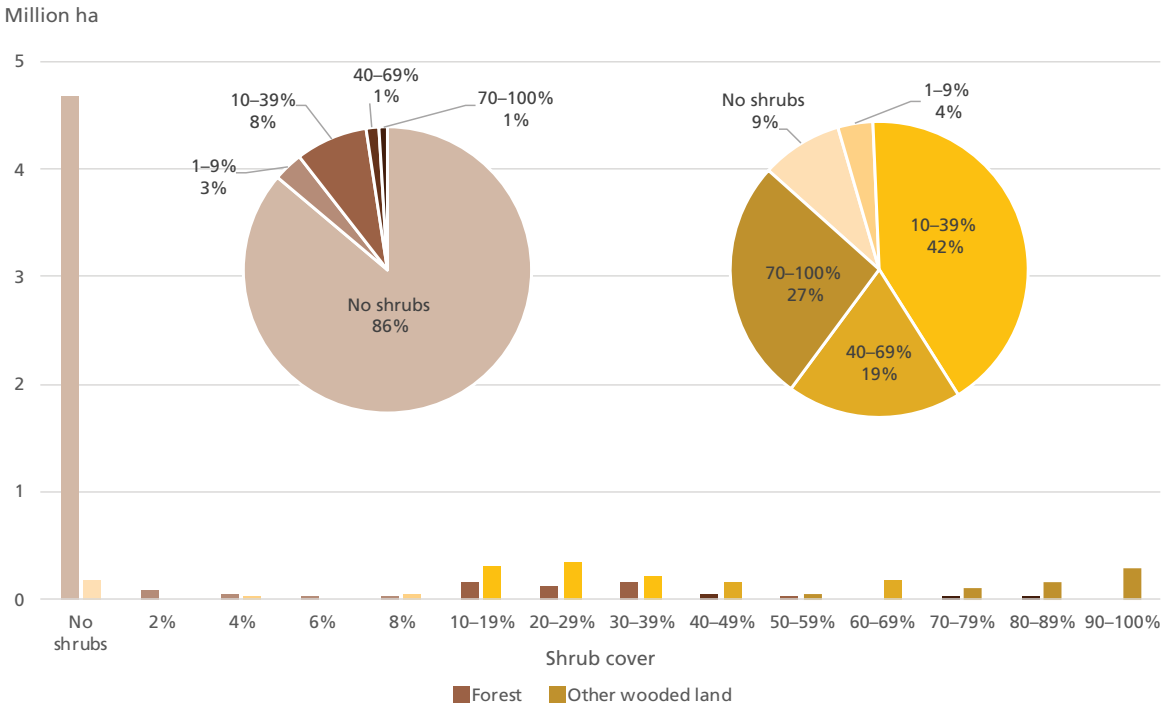
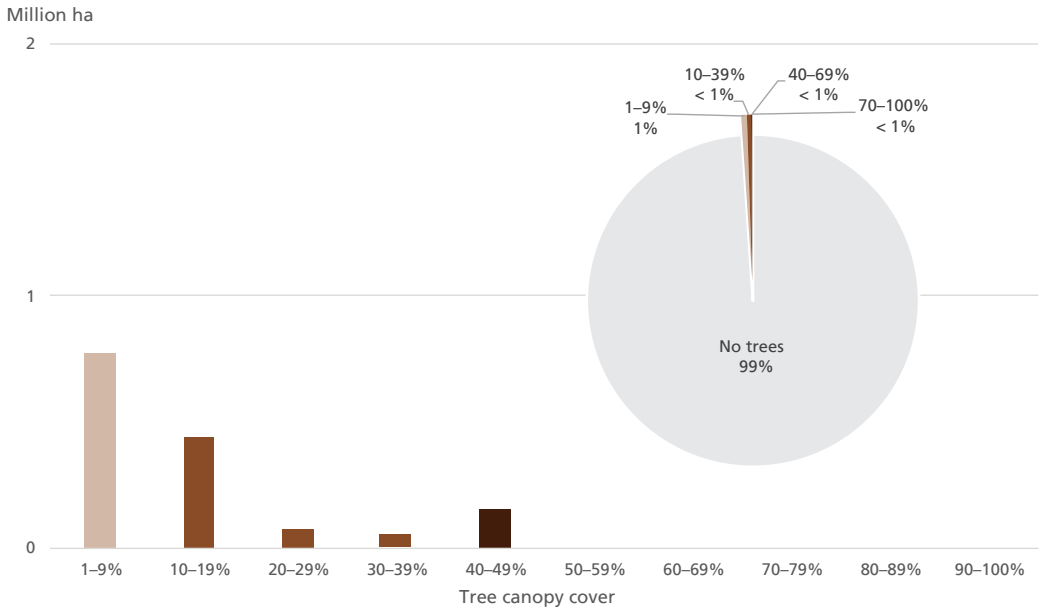


FIGURE 33. Tree canopy cover in other land in "presumed drylands" of the Qinghai–Tibet Plate



3.3.3 Land degradation on the Qinghai–Tibetan Plateau

3.3.3.1 Human impacts and drivers of degradation

The high-altitude location and harsh environmental and climatic conditions make the QTP a very fragile system that is both sensitive to human impacts (Li *et al.*, 2020) and recovers slowly (Liu *et al.*, 2019).

During the last two centuries, the QTP suffered numerous natural disasters leading to losses of livestock and socioeconomic collapse (Shang *et al.*, 2014). However, over the second half of the last century, improved infrastructure and market demand resulted in a steady growth of the livestock industry and improved socioeconomic development of the region, leading to the growth of both human and livestock populations (Shang *et al.*, 2014). At the same time, the region experienced changes from traditional mobile pastoralism towards more sedentary pastoralism, encouraged by some national level policies. These processes resulted in a rise in overgrazing and land degradation through impacts on vegetation structure, soil erosion and landscape fragmentation (Li, G.Y. *et al.*, 2019, Li, H.D. *et al.*, 2019, Li, Y. *et al.*, 2019). By 2005, there were an estimated 30 million sheep and goats and 12 million yaks on the QTP, which is considered to be well beyond the ecological carrying capacity of this area (Harris, 2010; Shang *et al.*, 2014).

Large-scale degradation on the QTP started particularly in the 1980s and gained speed in the 1990s (Li *et al.*, 2013a). Besides human population growth and the need to sustain livelihoods, grassland cultivation, vegetation harvesting for fuel and the supply of traditional medicines, as well as industrialization and urbanization, led to an increase in arable land and degradation of native vegetation (Cao *et al.*, 2019; Fayiah *et al.*, 2020). Population growth in China and increased demand for meat products has contributed to growing pressures on grassland areas. The development of infrastructure has also contributed to degradation, including landscape fragmentation, air and water pollution, and damage by heavy machinery. Between 2000 and 2019, major road development across the QTP increased 3.6-fold (Fayiah *et al.*, 2020).

3.3.3.2 Consequences of land degradation

Estimates of the current level of degradation in the region vary between different authors, from 33 percent (Cao *et al.*, 2019) to 50 percent (Li *et al.*, 2013a; Wu *et al.*, 2014; Wang *et al.*, 2016), and some studies suggest that most of the QTP grasslands show higher levels of degradation (Ren *et al.*, 2013; Wang *et al.*, 2015b). This has negative consequences for the ecosystem functions and services delivered in the QTP, particularly primary production, nitrogen recycling and carbon storage (Wen *et al.*, 2013).

Degradation in the QTP in general leads to reduction of grassland productivity (Wen *et al.*, 2013) and has negative impacts on biodiversity (Fayiah *et al.*, 2020). Furthermore, degradation leads to decreased vegetation cover, plant biomass and productivity (Wen *et al.*, 2013; Gong *et al.*, 2017), decreased soil fertility (Wang *et al.*, 2014), as well as diminished species diversity, composition and distribution (Lu *et al.*, 2017). For example, the above-ground biomass has decreased annually by 4 to 16 kg/hectare between 1987 and 2004 in the "Three Rivers" area of the QTP (Li *et al.*, 2013a). Degradation of the QTP grasslands also has significant impacts on the chemical and physical properties of soils, leading to decreases in soil organic carbon, microbial biomass carbon and total soil nitrogen (Su *et al.*, 2015; Lu *et al.*, 2017; Peng *et al.*, 2018; Zhang *et al.*, 2019).

It has been estimated that around 42 percent of soil organic carbon, 33 percent of total nitrogen and 17 percent of total phosphorus have already been lost in the QTP due to degradation (Liu *et al.*, 2019; Dong *et al.*, 2020b; Fayiah *et al.*, 2020). Moreover, degradation alters the soil microbial community. For example, Zhang *et al.* (2016) have shown that yak overgrazing on alpine meadows significantly reduced the richness of soil bacterial species and suggested that this could be a reason for further degradation of above-ground vegetation, because loss of soil microbial diversity may lead to a decrease in the availability of soil nutrients. Finally, changes in soil properties have dramatic consequences for livestock (decline in plant productivity), humans (economic effects) and rivers (pollution).

3.3.4 Opportunities and best practices for contributing to land degradation neutrality

On the QTP, numerous policies and initiatives have been introduced to tackle land degradation, with a focus on decreasing the grazing pressure on grasslands and on restoration and rehabilitation of degraded land.

3.3.4.1 Policies and initiatives to decrease grazing pressure and improve livelihoods

In the past, traditional yak grazing management, as practised by nomads, involved the movement of animals throughout the year. However, in more recent times, this has been replaced by transhumance, i.e the practice of moving livestock to different landscapes in different seasons in order to attain favourable forage conditions. As a result, during the winter, herders now live in houses, while their livestock are fed in barns (Long *et al.*, 2008). This process of sedentarization has been applied in the QTP to limit the issue of grassland degradation, though this is not without controversy politically, socially or ecologically.[34] It is considered easier to support sedentary herders through measures, such as grassland cultivation to address forage shortages in winter, applying techniques to control small mammals and investing in winter sheds to decrease livestock mortality (Yan, Wu and Zhang, 2011; Dong *et al.*, 2007; Wang *et al.*, 2015a). Some governmental programmes aim at moving the herders to cities, so as to make them more likely to adopt non-grazing livelihoods. However, such approaches are very controversial, as they uproot people from their culture and often lead to conflicts. There is also a risk of marginalisation when pastoralists move to cities, particularly when alternative livelihoods are not provided (Foggin, 2008).

Grazing bans have also been introduced in the most degraded places in the QTP, leading to dramatic changes in the local people's lifestyles (Dong *et al.*, 2007). While there is research showing that temporary bans on grazing can help vegetation recover, grazing is an integral part of the QTP's socio-ecological system and total ceasing of grazing in some areas may lead to negative consequences, such as reduced biodiversity (Milchunas, Sala and Lauenroth, 1988; Wang *et al.*, 2015a). In addition to grazing bans in severely degraded areas, programmes for reducing the number of grazing animals have been introduced, in order to help restoration (Papanastasis, 2009; Wang *et al.*, 2015a). Another strategy is to temporarily fence particular areas during summer and autumn, and then to use them as forage reserves in winter and spring, so as to reduce livestock pressure (Wang *et al.*, 2015a).

Both sedentarising herders and introducing grazing bans or limits on animal numbers have been much debated. It is argued that livestock mobility, based on traditional governance systems, is a critical aspect of pastoral systems that enable their sustainable long-term management (FAO, 2016a). Mobility ensures access to fodder, water supplies and shelter, while enabling avoidance of

[34] https://www.nytimes.com/2015/07/12/world/asia/china-fences-in-its-nomads-and-an-ancient-life-withers.html

extreme weather conditions or conflicts, hence providing adaptive capacity to climate change. At the same time, mobility helps in optimising the use of resources across the landscape and avoiding degradation (IUCN, 2011). Moreover, mobility is part of the Indigenous people's culture and their ethnographic heritage, which is reflected in their traditions, local festivals, gastronomy and architecture (Gregorio ValascoGil, personal communication, 2021). It is also highlighted that traditional and indigenous knowledge should be taken into account while developing policies and strategies for reducing degradation and that interventions need to consider Free, Prior and Informed Consent (FPIC) of Indigenous populations (FAO, 2016b). Thus, it is crucial to establish adequate participatory processes and promote trust as the basis for conflict avoidance and resolution (FAO, 2016a).

Implementation of market-based approaches, which do no take customary local governance systems into account, may result in negative impacts on livestock productivity and production costs, as well as lead to conflicts (Gongbuzeren, Zhuang and Li, 2016). It may also have unintended negative effects and exacerbate degradation (FAO, 2016a). To reverse the disturbing trends of degradation, the International Centre for Tibetan Plateau Ecosystem Management (ICTPEM) in China's Gansu Province, with support from the World Bank, has been working on a holistic approach to pastoralism, so as to assist herders improve their land management.[35] Their collaboration has enabled PES and measures such as temporary fencing of the most degraded areas to restore alpine grasslands, constructing habitat stands and developing a breeding programme for native hawks, which are natural predators of small mammals. According to ICTPEM, all these measures have been implemented in close cooperation with local communities, using a comprehensive participation process to build trust among local herders. It was highlighted that such an approach requires long-term efforts, as it was found that the programme had a significant net income effect, but only 10 years after implementation.

3.3.4.2 Sustainable land management practices

Various projects promoting sustainable land management have been implemented in the QTP. For example, an FAO project aiming at development of Verified Carbon Standard (VCS) methodology for sustainable grassland management[36] is supporting herders in better management of their animals and grasslands that leads to climate change mitigation. The VCS methodology quantifies reductions in emissions from activities such as limiting the time and number of grazing animals or rotation of grazing animals between winter and summer pastures. Presently (2021) the project is being implemented in Qinghai Province.

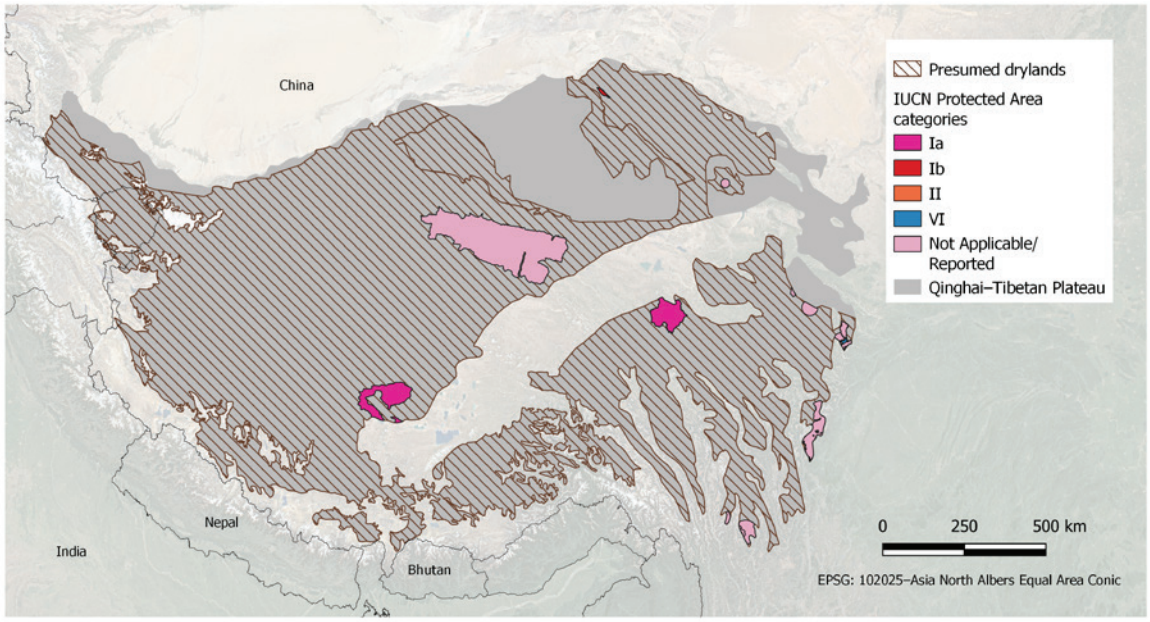
Another project, within a large international initiative 'Community approaches to sustainable land management and agroecology practices', which was implemented in Shiqu County to improve rotational grazing, led to increased capacity in local communities for more sustainable land management (UNDP, 2017). According to UNDP, the project created and disseminated a manual on sustainable wild medicinal plant harvesting, reduced damage to natural vegetation and installed wooden posts for attracting predatory birds that control small rodents. It also organised training and provided financial support for development of alternative livelihoods.[37]

3.3.4.3 Restoration, rehabilitation and conservation

Areas designated as protected areas in this region are relatively limited. In the area near Sichuan, the areas defined as "presumed drylands" fall inside the World Heritage site that corresponds to the Sichuan Giant Panda Sanctuaries – Wolong, Mt Siguniang and Jiajin Mountains. There is also only one other World Heritage site in the Qinghai area of the plateau and a few other Ramsar sites throughout the Qinghai–Tibetan Plateau. The region's protected areas, according to IUCN classification, are shown in Figure 34. The total area of protected areas, both at national and international levels, within Ramsar sites and World Heritages sites, comprise only slightly over 4 percent of the "presumed drylands" in the QTP. When only IUCN categories of protected areas were taken into account, this area was reduced to approximately 1 percent.

[35] https://ourworld.unu.edu/en/high-and-dry
[36] http://www.fao.org/in-action/sustainable-grassland-management-offers-a-better-future-for-qinghai-herders/en/
[37] https://www.thegef.org/sites/default/files/publications/SGP-Agroecology%20Publication-Digital.pdf

FIGURE 34: Protected areas of international importance in the "presumed drylands" of the QTP



Sources: UN Map, 2018; UNEP-WCMC, 2007; Olson *et al.*, 2001; IUCN and UNEP-WCMC, 2021

Due to the harsh environmental conditions and thus slow vegetation restoration and pedogenic processes, the recovery of degraded pastures on the QTP is difficult (Liu *et al.*, 2019), and there are no data available for the extent of grassland restoration. During the last three decades, different large-scale programmes aiming at grassland restoration have been implemented, all together covering over 23 percent of the grassland areas in China (Lu *et al.*, 2018). Examples of such projects implemented on the QTP include the national-level project 'Restoring Grasslands of the Qinghai–Tibetan Plateau 2017–2019'[38] and the local-level project 'Retire Livestock and Restore Pastures', which started in 2003 (Fayiah *et al.*, 2020). The latter used a combination of rotational grazing and exclusion approaches to mitigate grassland degradation. A follow-up study, evaluating the results of this project, concluded that temporary grazing exclusion on degraded areas was effective in increasing vegetation cover and the height of alpine grasslands, and resulted in higher biomass, indicating increased productivity, but had no effects on species diversity (Yan and Lu, 2015). Key grassland restoration approaches employed on the QTP, usually as a combination of different methods, include the revegetation of degraded land with cultivated grasslands, the selection of native grass species for restoration, sowing a mix of grasses and other species, weeding, irrigation and fertilization (Dong, Q.M. *et al.*, 2013; Dong, S.K. *et al.*, 2020a). Artificial seeding and the introduction of pioneering species are particularly needed in heavily degraded areas and bare land (Li *et al.*, 2013a).

It has been shown that on the QTP, revegetation can help restore total nitrogen and carbon in soils in grasslands (Su *et al.*, 2015). Temporary grazing exclusion and fencing have also demonstrated positive effects in reversing degradation, and increasing plant cover, water retention, soil organic carbon and species diversity (Li *et al.*, 2013b; Wang *et al.*, 2019). In general, many of the restoration projects launched on the QTP have shown positive results and helped to mitigate degradation and increased net primary production of the grasslands in this area (Cai, Yang and Xu, 2015).

As small mammals, such as the plateau pika (*Ochotona curzoniae*) are considered by some as important drivers of land degradation on the QTP, management techniques to control them are one of the means to decrease degradation (Li *et al.*, 2013a). Governmental programmes implemented on the QTP commonly promote poisoning of small mammals (Wang *et al.*, 2015a). However, this can have negative environmental impacts, such as killing their natural predators (Harris, 2010). Therefore, the use of traps and other ways of physically killing them is recommended instead. Some governmental programmes also promote biological controls by building nests and platforms for birds of prey to encourage the presence of eagles and hawks, i.e. their natural predators (Wang

[38] https://www.cabi.org/projects/restoring-grasslands-of-the-qinghai-tibet-plateau/

et al., 2015a). More recent research highlights the important role that small mammals, such as the plateau pika, play in maintaining alpine grasslands through influencing plant species richness and plant above-ground biomass, and providing other ecological benefits in the QTP (Pang, Wang and Guo, 2021; Zhao *et al.*, 2020). Furthermore, four species of antelope also play indispensable roles in regulating the different ecosystems on the plateau: Przewalski's gazelle (*Procapra przewalskii*), the Goitered gazelle (*Gazella subgutturosa*), the Tibetan gazelle (*Procapra picticaudata*) and the Tibetan antelope (*Pantholops hodgsonii*), but are threatened by human impact and climate change, and require protection (Zhang *et al.*, 2021).

The use of PES was also suggested as a strategy to support restoration and ecosystem conservation in the QTP (Wang and Wolf, 2019; Wang *et al.*, 2016). As such, Huang *et al.* (2018) evaluated the implementation of the PES programme 'Three River Sources ecosystem restoration program' in the Northeastern QTP, where central and local government funding was used for ecological conservation and restoration, research and monitoring, as well as the development of local infrastructure to improve conditions for local communities. The programme contributed to restoration efforts, resulting in increased grassland areas and decreased desert ecosystems, as well as a rise in net productivity (from around 180 to 210 gC per square metre per year) and an increase in water and wetlands, and soil retention (9 percent and 32 percent, respectively, between 2004 and 2012) (Shao *et al.*, 2017; Huang *et al.*, 2018; Sheng *et al.*, 2019). The programme also compensated immigrants and improved the living standards of 86 percent of them (Huang *et al.*, 2018).

Besides different restoration and rehabilitation initiatives, other types of projects are also being implemented in the QTP. For example, a GEF project to strengthen effectiveness of the protected area system was implemented in Qinghai Province to support globally important biodiversity.[39] It resulted in a significant improvement in the protected area system in this province, as well as stable or slightly increasing populations of indicator species. It also led to better management and improved funding (from USD 2.88 million to USD 8 million per year), as well as increased employment in the protected areas, with over 67 percent of new staff representing ethnic minorities and 26 percent being women. Another GEF project 'Partnership to Combat Land Degradation in Drylands'[40] was implemented in nine Chinese provinces, including Qinghai, between 2008 and 2012, and supported long-term capacity building for simultaneously addressing land degradation, biodiversity conservation and poverty alleviation. For example, the use of innovations such as methane tanks for biogas in pilot areas contributed to reducing the pressure on vegetation and improved carbon storage, and less pollution and degradation, while participatory planning helped local communities balance livelihood and productivity needs with sustainability considerations, leading to a decrease in conflicts.

In summary, this chapter provided an overview of the status and challenges that "presumed drylands" face in the three study areas. However, catalysing different LDN solutions requires incentives for concrete actions at different levels. Demonstrating the value of these lands for the economy, livelihoods and human well-being can help highlight their importance and add to our understanding of how to invest in them so as to avoid further degradation. In the next chapters, a cost–benefit analysis is presented for two of the study areas, the Cerrado and the Miombo–Mopane woodlands, in order to demonstrate the potential contribution of "presumed drylands" to LDN targets, which in turn can help transform these dryland-like systems into more sustainable ecoregions (Haddad, Ariza and Malmer, 2021). Key approaches for sustainable rangeland management in the QTP are also highlighted based on available literature.

[39] https://www.thegef.org/project/cbpf-strengthening-effectiveness-protected-area-system-qinghai-province
[40] https://www.thegef.org/publications/knowledge-series-china-gef-partnership-combat-land-degradation-drylands

CERRADO
FOREST
©FAO/Anne Branthomme

4. Valuing the case for halting land conversion and land degradation within "presumed drylands" of the Cerrado region

4.1.1 Setting the scene

The Cerrado itself holds one-third of Brazil's biodiversity and about five percent of the world's flora and fauna. An important aspect of the Cerrado's vegetation is not only its high diversity of tree species (Haridasan, 2008; Castro *et al.*, 1999), but also the coexistence of trees, shrubs and herbaceous layer (Gardner, 2006). Any hectare of the Cerrado can have up to 70 tree and shrub species.

In recent years, the Cerrado has become the largest agricultural frontier in the country. The expansion of soy production and cattle ranching has been the primary driver of habitat conversion in the Cerrado in recent decades, resulting in the loss of approximately half the biome's native vegetation (TNC, 2019).

Box 6
Conditions for successful adoption of agroforestry systems

The Cerrado has been dubbed Brazil's *birthplace of waters* (Sax and Angelo, 2020), as it supplies water to six of the country's eight largest watersheds, eight of the country's twelve river basin districts, and three of the world's largest and oldest aquifers

Source: Rekow, L. 2019. Socio-ecological implications of soy in the Brazilian Cerrado. Challenges in Sustainability, 7(1): 7–29; Sax, S. and Angelo, M. 2020. Soy made the Cerrado a breadbasket; climate change may end that. Mongabay (https://news.mongabay.com/2020/05/soy-made-the-cerrado-a-breadbasket-climate-change-may-end-that/)

Soy accounts for 90 percent of cultivated crops in the Cerrado, and in 2020, Brazil surpassed the United States of America to become the world's largest soy producer (USDA, 2020). This prodigious output can partially be attributed to crop intensification on lands already in production (Garrett *et al.*, 2018), much of it in the southern Cerrado, but also in a drier area to the north in MATOPIBA – an acronym for the states of Maranhão, Tocantins, Piauí and Bahia (Sax and Angelo, 2020) – most of which belong partly to the "presumed drylands" region of the Cerrado, as shown previously in Figure 17.

Moreover, climate modelling experiments have shown that preserving remnant Cerrado vegetation is essential not only to climate stability in the Cerrado, but also to the Amazon downwind (Pires and Costa, 2013; Malhado, Pires and Costa, 2010; Coe *et al.*, 2013), as air masses moving westward over the Cerrado transport evapotranspired water over the Amazon Basin (Spracklen, Arnold and Taylor, 2012). Therefore, land degradation in the Cerrado is not only threatening the sustainability of agricultural production in both the Cerrado and the Amazon (Spera, Winter and Chipman, 2018), but is impacting traditional communities, who have seen agribusiness expansion encroach upon their territories and restrict access to lands used for vegetable and livestock farming, and resources for craftworks such as grass weaving (TNC, 2019; Sax and Angelo, 2020).

4.1.2 Measuring land degradation

The valuation assessment followed LDN indicators for assessing the quantity and quality of land-based natural capital, namely: land cover (land cover change); land productivity (net primary productivity, NPP) and carbon stocks (soil organic carbon, SOC).

The associated metrics are quantified for each land type at the baseline period set, i.e. in this case 2019, the most recent year for which data on land cover were available. According to the one-out, all-out principle in Cowie *et al.* (2018) used to evaluate the indicators that determine LDN status, degradation occurs when (compared with the baseline):

1. SOC decreases significantly;
2. NPP decreases significantly; or
3. Negative land cover change occurs.

Since LDN indicators and associated metrics are considered complementary components of land-based natural capital, they are quantified and evaluated separately. As such, gains in one of these measures cannot compensate for losses in another. If one of the indicators/metrics shows a negative change, LDN is not achieved, even if the others are substantially positive. Using this approach in this study, land cover change is used as the main indicator of land degradation. Specifically, any transition from forest cover or native vegetation to cropland is considered as a negative change, since cropland can support fewer ecosystem services (Cowie *et al.*, 2018).

On this basis, it is possible to conceive a LDN scenario, whereby cropland expansion occurs only on low productivity pastures instead of through conversion of natural vegetation (Sims *et al.*, 2020). In the following valuation study, the economic implications of continued clearing of native Cerrado land for pastures and cropping are assessed through a business-as-usual (BAU) scenario. This is compared to a LDN scenario, in which the expansion of soy takes place on degraded pastures and where there is no further clearing of natural vegetation. The impact and value of changes in carbon emissions in the two scenarios are also assessed with reference to the 2021–2050 timeframe. Finally, incentives and policies that may be needed to help protect native vegetation from further deforestation are discussed.

4.1.2.1 Valuation scenarios

As soy is highly versatile in usage and extremely efficient in yield, this crop has witnessed a significant expansion in recent decades (IDH, 2020). However, with important feedbacks between land cover changes, regional rainfall and land productivity (Soterroni *et al.*, 2019), the question is whether crop production systems risk being compromised.

In the assessment carried out here, this hypothesis is analysed by assessing the feedback between land clearing under BAU practices, weather patterns, agricultural production and the profitability of soy farming (BAU scenario).

The expansion of cropland, however, does not have to occur at the expense of native vegetation. According to Carneiro and Costa (2016), there are at least 25.4 million hectares of land already cleared in the Cerrado that are suitable for accommodating agricultural expansion. Moreover, there are approximately 18.5 million hectares of degraded pastureland (ICONE, 2016; Andrade *et al.*, 2015), which is sufficient to meet the projected expansion of soybean as per the predictions in this chapter and those of Andrade *et al.* (2015).

In particular, by focusing on the expansion of soy production onto existing, low-productivity cattle pastures, it may be possible to increase agricultural output while conserving remaining habitat, as suggested by several studies (TNC, 2019; Strassburg *et al.*, 2014; Soterroni *et al.*, 2019). As the productivity of Brazilian pastures is estimated at only 32–34 percent of their potential (Strassburg *et al.*, 2014), the loss of pastureland could be offset by increases in pasture productivity. With respect to the Cerrado, cattle stocking rates could increase, on average, from 1.1 to 2.6 animal units/hectare (Brito *et al.*, 2018). The Cerrado is therefore a critical area when it comes to the recovery of degraded lands (CGEE, 2016). In this LDN scenario, there is no further clearing of native Cerrado vegetation, whether for pastures or crops, and cropland expansion occurs only over low-productivity pastures instead of natural vegetation (Box 7).

For the purpose of Cerrado assessment, the costs and benefits to farmers are assessed for expanding soy on degraded pastures between 2021 and 2050, instead of clearing native Cerrado vegetation. While the focus here lies on the profitability per hectare of soy farming, the impact and value of changes in greenhouse gas emissions shall likewise be assessed, since the Cerrado serves as a vital store of carbon (Gasparinetti *et al.*, 2020).

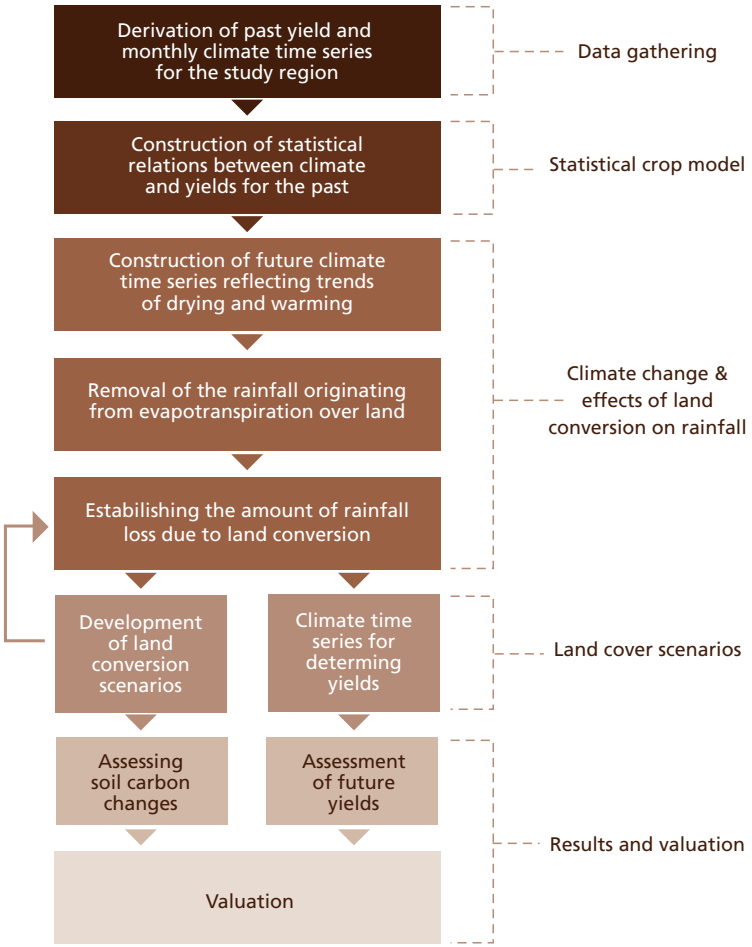
Box 7
Conditions for successful adoption of agroforestry systems

LDN scenario	BAU scenario
Between 2021 and 2050, no further clearing of native Cerrado vegetation will take place, whether for pastures or crops – and cropland expansion will only occur over low productivity pastures instead of natural vegetation.	Between 2021 and 2050, an additional 16.7 million hectares of native Cerrado vegetation will be cleared and used for soy cropping.

4.1.2.2 Study methods and design

The models and results presented in this paper are based on a comprehensive representation of the interactions between land cover changes, rainfall and agricultural soy yields within the "presumed drylands" ecoregion of the Cerrado. Below is the summary of the methodological steps followed in this assessment (Figure 35):

Figure 35: Steps in the biophysical modelling process prior to valuation


Derivation of past yield and monthly climate time series for the study region
Construction of statistical relations between climate and yields for the past
Construction of future climate time series reflecting trends of drying and warming
Removal of the rainfall originating from evapotranspiration over land
Estabilishing the amount of rainfall loss due to land conversion
Development of land conversion scenarios
Climate time series for determing yields
Assessing soil carbon changes
Assessment of future yields
Valuation
Data gathering
Statistical crop model
Climate change & effects of land conversion on rainfall
Land cover scenarios
Results and valuation

- **Step 1:** Historical data were gathered based on annual soybean yields, as well as data on monthly temperature and precipitation from peer-reviewed literature (see Appendix 3 for an overview of data sources). On this basis, a statistical model associating climatic variables and yields was elaborated and tested for its ability to capture the evolution of past soybean yields.

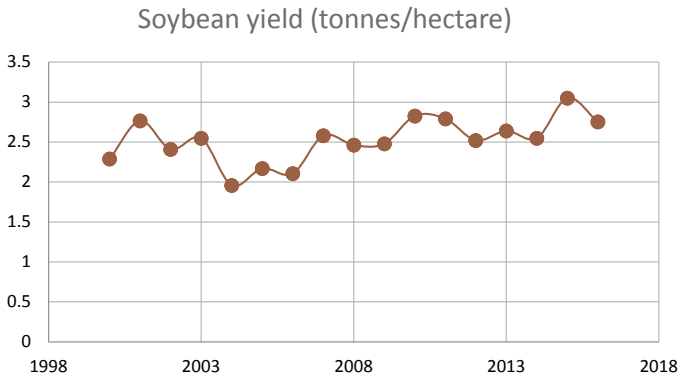
- **Step 2:** Time series of future rainfall and temperature were constructed, including the expected effects of climate change and increases in the frequency of droughts.
- **Step 3:** Given the particularities of moisture transportation in the Cerrado region, the fraction of rainfall in the Cerrado that originates from evapotranspiration over land was evaluated. This aspect is fundamental for establishing the amount of rainfall that has historically been lost due to land conversion in the Cerrado.
- **Step 4:** Past land cover trends (during which both the annual amount of precipitation and the rate of land conversion are already known) were extrapolated in order to make predictions of land use changes in the BAU and LDN scenarios. The land conversion scenarios can then be used to determine changes in precipitation levels in "presumed drylands" of the Cerrado, in addition to those expected from underlying climate change. As such, underlying climate change was accounted for by investigating temperature and drought frequency changes using climate models obtained from the literature.
- **Step 5:** The time series of precipitation and temperature were then fed into the statistical model developed so as to derive levels of future soybean yields. The land conversion scenarios are also used to determine changes in carbon emissions.
- **Step 6:** Finally, the changes in crop yields were valued in terms of the profitability of soy farming and the monetary value of changes in carbon emissions.

4.1.2.3 Land degradation in the Cerrado and the value of lost agricultural productivity

Past data on yields for the Cerrado region

Historical soybean yields within "presumed drylands" of the Cerrado biome were derived from Iizumi *et al.* (2020) for the period 2000–2016. This assessment was carried out by overlaying gridded yearly yield data for soybeans with the geographical boundaries of the Cerrado's "presumed drylands", using the database from FAO (2019), and calculating the respective yearly time series of the average yields observed (Figure 36). Between 2000 and 2016, average yields in "presumed drylands" of the Cerrado increased from 2.3 tonnes/hectare to 2.8 tonnes/hectare. Yields were particularly low in 2016 due to low precipitation, showing the important influence of climate on soybean yields in the Cerrado.

Figure 36: Calculated trends in soybean yield for "presumed drylands" of the Cerado, based on data from Iizumi and Sakai (2020)

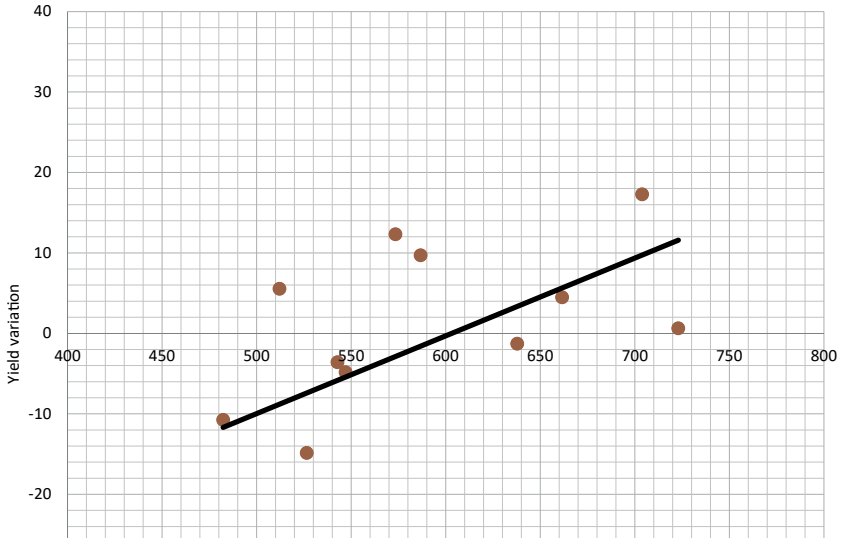


Establishing a statistical crop model

Inter-annual crop yield variations are both driven by technological advances and the effects of climate, notably monthly precipitation and temperature. To better understand the impacts on land productivity, it is necessary to be able to separate these two effects. In order to isolate the influence that climate exerts on yields, the crop yield data were detrended, using a first-difference approach.[41] This is a flexible and common method used in time-series data to minimize the

[41] From each value one subtracts the value in the previous year. In this case, the subsequent analysis focuses only on year-to-year changes so that the effects of long-term trends are minimized. Any predictor variables are also transformed to first differences in order to compare with yields. https://www.climate-policy-watcher.org/crop-yield/trend-removal.html

FIGURE 37: Relationship between soybean yield and precipitation



influence of technology (Lobell and Field, 2007). On the basis of the detrended crop yield data, the assessment team performed a yield regression incorporating the climate model, precipitation levels and temperature. To find the best model fit, various monthly aggregations of precipitation and temperature were made, taking account of the planting, growing and harvesting calendar of soy.[42] September to December precipitation levels were the best predictors of crop yields in the following year, significant at $p<0.05$ ($p = 0.024$) and R^2 of 0.36 (Figure 37). Below 550 mm of rainfall, between September and December, there is a negative effect of precipitation on soybean yields.

The yearly percentage variation in soybean yields due to precipitation (Py_t) in "presumed drylands" of the Cerrado is given by equation 1 below:

$$Py_t = - 0.58 + 0.096 * Sep–Dec\ (mm) \qquad \text{(eq. 1)}$$

It implies that as precipitation decreases, yields decrease. For every 100 mm decrease in precipitation between September and December, yields decline by 9.6 percent (and vice versa) the following year. The effect of temperature on soybean yields was also analysed. The maximum average temperature from December to February – typically the months when pod-filling takes place – is negatively correlated with yearly variation of yield. However, the strength of the correlation is weak and accounts for a maximum of 10 percent of the yearly variation in the detrended yield.

As per equation 2, the percentage variation in soybean yields in tonnes/hectare due to temperature (Ty_t) in "presumed drylands" of the Cerrado is given by:

$$Ty_t = - 10.99 + 0.02859 * Dec–Feb\ (tmax) \qquad \text{(eq. 2)}$$

It implies that for every 1 °C *increase in maximum temperature between September and December, soybean yields decrease by 2.8* percent the following year.

Finally, it is important to account for the effects of technological change on yields. Accordingly, a linear model is fitted with time as a single independent variable to the time series of soybean yield in "presumed drylands". The fit is statistically significant with an adjusted R^2 of 0.3 and a slope of 0.0305. Analytically, the annual yield expected due to the effects of technological change on soybean yields (My_t) in "presumed drylands" of the Cerrado is given by equation 3 below:

$$Myt = - 58.7575 + 0.03053 * year \qquad \text{(eq. 3)}$$

The equation implies that technology and management practices have improved soybean yields within "presumed drylands" of the Cerrado by about 30.5 kg/year for each hectare of cultivated

[42] For example, early November is the main soybean planting period in Brazil, but stretches until December when early-planted soybeans start flowering and setting pods. February is the main pod filling month for soybeans and March the main soybean harvesting month. By April the soybean harvesting season is completed.

soybeans. Specifically, since the mid-1990s the Cerrado has witnessed an impressive increase in agricultural productivity as a result of the adoption of modern hybrid cultivars and increased use of fertilizers and lime, thus bringing productivity levels in the Cerrado up to similar levels as elsewhere in Brazil (The Economist, 2010[43]; Ray *et al.*, 2013). In 2016, the average soybean yield in the Cerrado's "presumed drylands" was 2.7 tonnes/hectare in comparison with 2.8 tonnes/hectare for the whole of Brazil.[44]

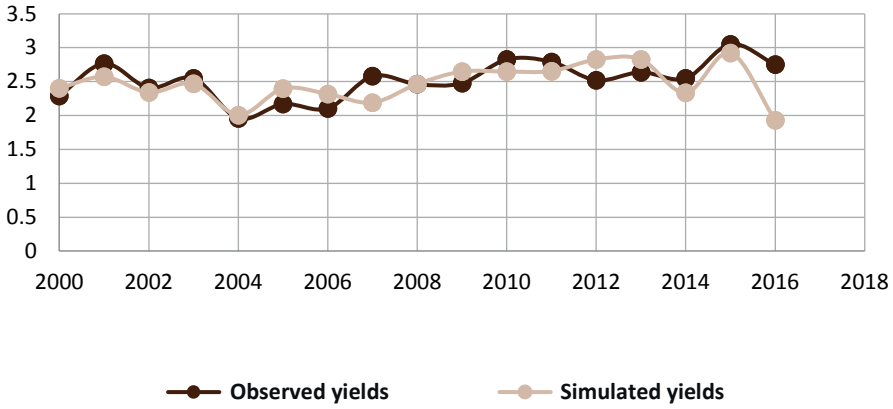
The final crop yield model presented integrates the results of the equations estimating the individual contributions of precipitation, temperature and technology. Accordingly, soybean yield (Syt) variation in time is given by equation 4:

$$Sy_t = My_t + (My_t * (Py_t * Ty_t)) \quad \text{(eq. 4)}$$

The equation implies that My_t is the expected yield driven by technological improvement, Py_t is the fraction of yield variation attributable to precipitation and Ty_t is the fraction of yield variation attributable to temperature.

Having established the model presented, the capability of the model is assessed for reproducing the past variation of soybean yields in the Cerrado. Using historical values of precipitation, temperature and observed technological trends, the historical yields of soybeans are simulated in "presumed drylands" of the Cerrado (Figure 38), applying the set of equations above. As such, simulated yields are a good reflection of actual yields, providing confidence in the regression estimates.

Figure 38: Observed and simulated soybean yields in the "presumed drylands" of the Cerrado



4.1.3 Climate change and droughts in the Cerrado and effects of land conversion

4.1.3.1 The effects of drought on precipitation and temperature in the Cerrado

Soy production relies on the availability of sufficient water in the soil. Most soy farms in the Cerrado are rainfed, with only a limited area under irrigation in Bahia. Soy production in the Cerrado is therefore highly vulnerable to the adverse impacts of agricultural drought, defined as the moment when soil moisture drops to levels that adversely affect the crop yield and agricultural profitability (DCI, 2020; Mannocchi, Todisco and Lorenzo, 2004).[45]

Quantifying how climate change drives drought is therefore pertinent to informing policy and adaptation planning. In order to make drought projections, the 15th percentile is used over a 4-month period of precipitation as a threshold for defining drought, following Ukkola *et al.*

[43] The Economist (2010). The Miracle of the Cerrado. Brazil has revolutionised its own farms. Can it do the same for others? https://www.economist.com/briefing/2010/08/26/the-miracle-of-the-Cerrado

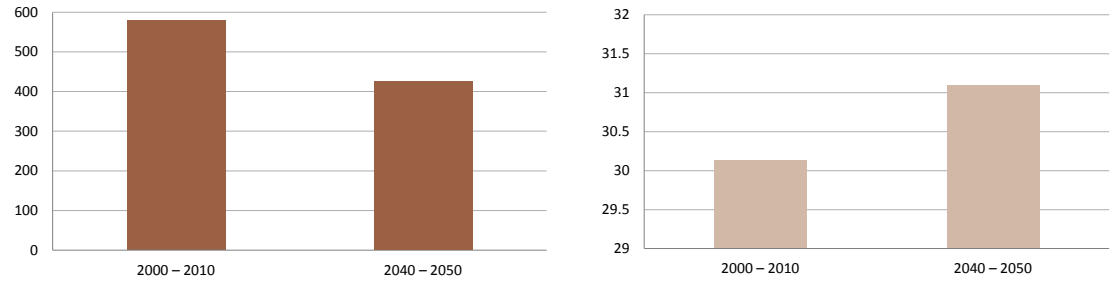
[44] http://www.fao.org/faostat/en/

[45] https://www.drycargomag.com/us-soybean-prices-trending-higher-on-dry-weather-brazilian-supply-tightness

(2020). Applying this to the case study here, drought years are evaluated as those in which the total precipitation level from September to December falls below the 15th percentile precipitation of the same months in the 2000–2019 timeframe. For the "presumed drylands" of the Cerrado study area, this is equivalent to 480 mm of precipitation from September to December.

Using this threshold, a total of three drought years were identified in "presumed drylands" of the Cerrado between 2000 and 2019. If no further climate change took place, one would expect 4.5 drought years during the 2020–2050 timeframe. Under the Representative Concentration Pathway 4.5 (RCP4.5),[46] drought frequency in the Cerrado is projected to increase by 1.8 by 2040, resulting in approximately 8.1 drought years between 2020 and 2050 (Rodrigues *et al.*, 2020). The predicted increase in drought frequency is partly attributable to changes in global GHG concentrations and partly due to expected land use changes. Double counting the impact of land use changes on climate change is avoided as explained by the methodology in Annex 3. Historical time series of temperature and precipitation for the Cerrado were constructed using data from Abatzoglou *et al.* (2018) at a 4-km resolution and covering the 1958–2015 period (Figure 39).

Figure 39: Predicted changes in precipitation levels and maximum temperatures in the BAU scenario



Source: Abatzoglou *et al.*, 2018

4.1.3.2 Quantifying the relation between land cover and precipitation in the Cerrado

Land use and land cover affect regional climate feedbacks in the Cerrado, with land clearance decreasing the amount of water recycled to the atmosphere via evapotranspiration (ET) each year (Campos, 2018; Spera *et al.*, 2016). ET from single-cropping systems (for example, soybeans) is lower than from natural vegetation, except between January and February, the height of the soybean growing season. In double-cropping systems (for example, soybeans followed by maize), ET is similar to or greater than the natural vegetation throughout a majority of the wet season (December–May). During the rainy season, from October to April, when soy crops are grown, ET in agricultural areas is similar to those areas covered by native vegetation. However, in the dry season, the volume of ET in agricultural areas averages 60 percent lower than in areas with native vegetation (Spera *et al.*, 2016).

To assess the connection between land cover changes and precipitation in the Cerrado, data are used from a recent study by the University of Brasilia (Campos, 2018) that has linked deforestation to an 8.5 percent drop in yearly rainfall in the Cerrado over the last three decades. According to Campos (2018), the conversion of 86 million hectares of native vegetation (around 2.6 million hectares/year) into pasture or cropland, resulted in a 125 mm decrease (8.5 percent) in precipitation between 1977 and 2010. From September to December – the months that matter the most for agricultural production – the accumulated drop in precipitation is 17 percent (or about 0.51 percent/year). In other words, the clearing of 1 million hectares of natural vegetation leads to a 0.02 percent[47] drop in precipitation between September and December.

[46] Described by the IPCC as an intermediate scenario and projects a 2–3 degrees Celsius rise in global temperature by 2100.

[47] 0.51 percent drop in precipitation/2.6 million hectares conversion of native vegetation

This empirical relationship is used to estimate how future precipitation levels will change in the Cerrado as a result of continued degradation and land use conversion.

4.1.4 Land conversion and yield scenarios for the Cerrado

4.1.4.1 Past land cover change

Based on land use and land cover data from Souza *et al.* (2020), land use changes since 2000 are focused on within "presumed drylands" of the Cerrado study area and a linear extrapolation is used to estimate land cover changes within the 2020–2050 timeframe.

Between 2000 and 2019, cropland expanded by 14.3 million hectares in the Cerrado ecoregion (Table 8), resulting in an additional 0.75 million hectares/year. Within this timeframe, 9.1 million hectares of pasture were converted to cropland and some 7.4 million hectares were converted directly from native Cerrado vegetation (typically wooded savanna-like vegetation) to cropland (Table 9). The dominant land use conversion process is therefore from native Cerrado vegetation to pasture and from pasture to cropland. The total surface dedicated to pasture has declined slightly over the 2000–2019 period, with pasture covering some 61 million hectares in 2019 against 62.5 million hectares in 2000 (Table 8).

TABLE 8
Evolution of land cover/use change in millions of hectares between 2000 and 2019 for the Cerrado and the annual rates of change;

Land cover/use	2000	2005	2010	2015	2019	2000–2019 (total)
Cropland	11.3	15.7	17.9	22.6	25.6	+14.3
Cerrado**	71.1	67.5	66.2	63.2	60.0	-11.1
Grasslands*	18.5	17.9	17.5	16.9	16.4	-2.1
Pasture	62.5	63.2	62.6	61.1	61.0	-1.5
Forest	31.1	29.8	29.1	28.6	29.0	-2.1

**Cerrado refers to wooded savanna-like native vegetation; *Grasslands refer to native herbaceous vegetation, though the existence of exotic/invasive vegetation for the purpose of animal use cannot be excluded; Pasture refers to the portion of land that is fully dedicated to animals; Forest can be either forest plantation or native forest. *Source*: Souza *et al.* (2020).

TABLE 9
Land cover changes in millions of hectares in "presumed drylands" of Cerrado from 2000 to 2019

From	To	Total change (2000–2019)	Yearly change (2000–2019)
Cerrado	Pasture	7.4	0.39
Pasture	Cropland	9.1	0.47
Cerrado	Cropland	3.4	0.17
Forest/plantations	Cropland	0.5	0.03
Forest/plantations	Pasture	2.4	0.12

4.1.4.2 Projected land cover changes

In the absence of sweeping policy changes aimed at curbing the current degradation of the Cerrado ecoregion, a continuous loss of native Cerrado cover can be expected (Table 10, Figure 41). In particular, if the trend for the past two decades continues, cropland areas can be expected to expand from 34 to 49 million hectares by 2050 and largely at the expense of natural vegetation as shown in Figure 38 and Table 11.

Figure 40: Land cover/use and change in the Cerrado ecoregion under the BAU and LDN scenarios in millions of hectares

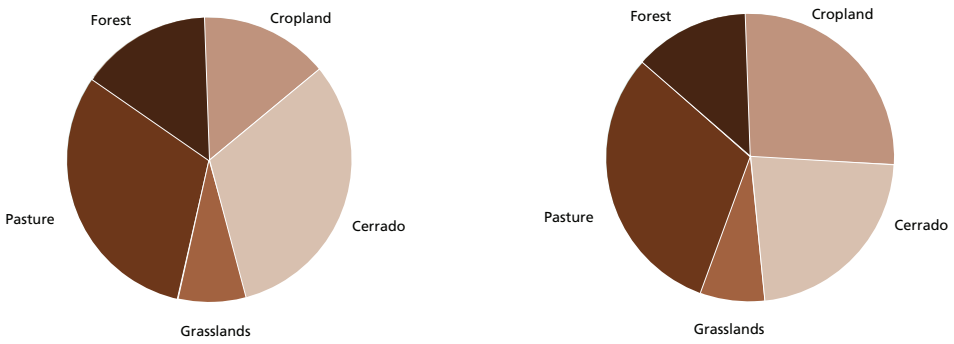
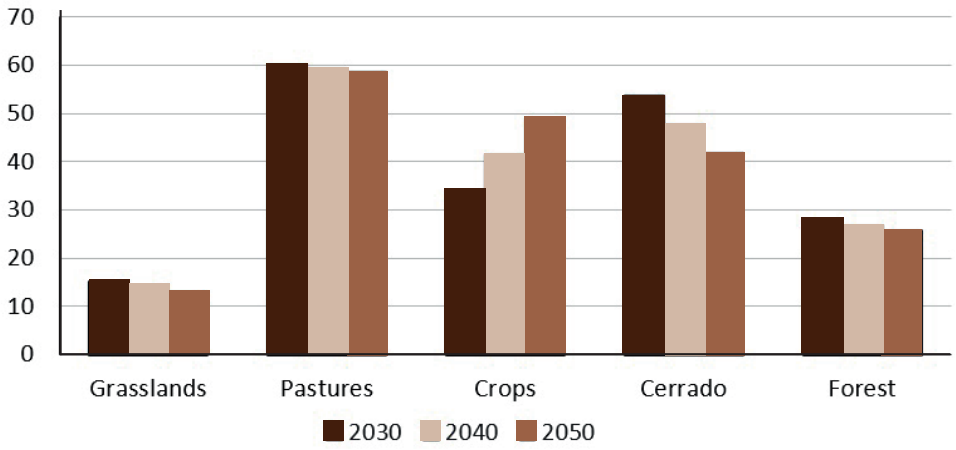


TABLE 10
Land cover change in millions of hectares under the baseline and business-as-usual (BAU) scenario for "presumed drylands" of the Cerrado

Land-cover/use (millions of hectares)	Baseline	BAU 2050	BAU Change (2021–2050)
Cropland	26.4	49.0	+23
Grasslands & pastures	77.2	71.6	-5.6
Cerrado	59.4	41.8	-18
Forest/plantations	28.9	25.7	-3

FIGURE 41: Projected land cover changes in the Cerrado ecoregion under business-as-usual (millions of hectares)



4.1.4.3 Yields and technological progress scenarios

Apart from changes in precipitation and temperature, technological progress also has an important impact on crop yields. According to an experienced soybean advisor (M. Cordonnier, personal communication, 2021), technological improvements have allowed soy crop yields to rise annually by an average of half a bushel per hectare, corresponding to approximately 33 kg per hectare. These values are in line with the statistical model set out above (Section 4.1.2.3, equation 4).

There are, however, reasons to expect that technological progress and yield improvements in the Cerrado will not continue to rise at the same pace as that observed over the last two decades.

The first reason for this is that yields cannot grow indefinitely and at some point, they will level off. This has been observed globally and for certain countries in particular (Ray *et al.*, 2012). For example, between 1961 and 2008, soybean yields stagnated across 24 percent of the global harvested area. According to the same study, soybean yields have not improved (within the same timeframe) on 58 percent of China's harvested soybean area and on 14 percent of Brazil's area.

Second, although large gains in productivity are possible initially through small investments in technology, in mature agro-businesses, each additional improvement in productivity is associated with a substantial investment. As such, soybean yields in Brazil are already comparable to those of highly efficient producers like in the United States of America, which means that any additional increase in productivity will be hard to achieve at a reasonable price. According to the above logic, it is reasonable to assume that technological progress in the Cerrado between 2021 and 2050 will be half of that observed in the 2000–2016 period. In making future yield projections, it is therefore assumed that technological advances will only contribute to a +0.015 tonnes increase per year (i.e. half that of the past increase).

4.1.5 Future changes of productivity in the Cerrado

Table 11 below summarizes the key components and assumptions underlying the BAU and LDN scenarios that feed into the productivity estimates and economic valuations set out here.

TABLE 11
Key components and assumptions underlying the integrated crop yield, weather and climate model

	Land conversion scenarios	Climate (2020–2050)	Technology
BAU	Cropland continues to expand into natural vegetation at past rates.	Average Sep–Dec precipitation drops to 426 mm. Dec–Feb average maximum temperature rises to 31.1 °C	Yields improve at half the historical 2000–2016 rate.
LDN	Future cropland expansion takes place only over degraded pastureland and there is no further clearing of native Cerrado vegetation.	Sep–Dec precipitation drops to 532 mm. Dec–Feb average maximum temperature rises to 31.1 °C	Assumption: Yields improve at half the historical 2000–2016 rate.

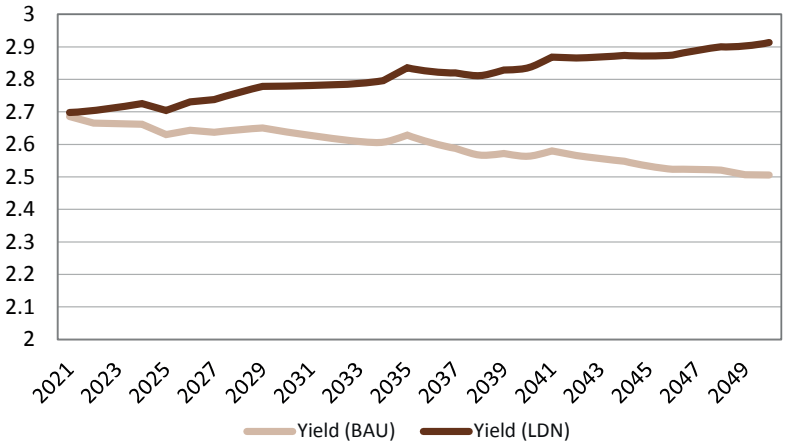
4.1.5.1 Changes in land use productivity under continued land degradation in the BAU scenario

Having estimated the projected changes in land use and crop yields under climate change, the future outcomes can be predicted on the productivity of soy in "presumed drylands" of the Cerrado as a result of land conversion (BAU scenario), versus a situation where all future cropland expansion occurs only on degraded pastureland (LDN scenario).

To do so, equations 1 through 4 are used (Section 4.1.2.3) and it is found that even though technological progress allows crop yields to increase, reduced precipitation levels will nevertheless lead to an absolute decline in soybean yields, from an average of 2.7 tonnes/hectare in 2020 to 2.5 tonnes/hectare by 2050. Under the LDN scenario, on the other hand, yields are expected to increase from 2.7 tonnes/hectare to 2.9 tonnes/hectare by 2050. Therefore, relative to a situation without deforestation of native Cerrado vegetation, business-as-usual practices will lead to a 16 percent decline in yields by 2050, as shown on Figure 42.[48]

[48] Both scenarios are driven by the same time series for temperature in which it is predicted that the frequency of future droughts will increase. For precipitation, however, the BAU scenario uses a modified version of the precipitation time series in which a penalty is introduced according to the magnitude of land conversion, as explained beforehand.

FIGURE 42: Simulated trend in soybean yields under BAU and LDN land conversion scenarios

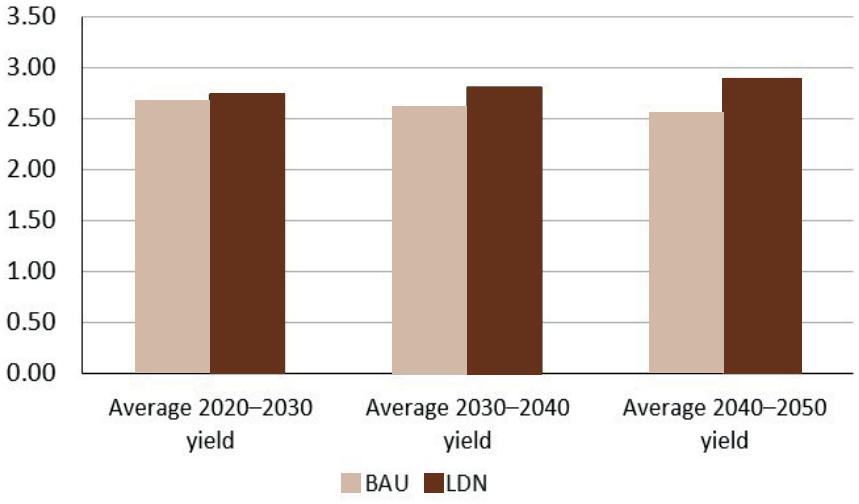


Note that Figure 42 is derived on the basis of simulations (the average yield of 1 000 runs from a distribution of possible outcomes) and that in reality, there will be more in-between yearly variation due to climate factors affecting a specific year. Figure 43 below shows average yields between 2020 and 2050 under the two scenarios in Table 12.

TABLE 12
Average crop yields in tonnes/hectare

	Yield in 2021	Yield by 2050 (BAU)	Yield by 2050 (LDN)
Yields (tonnes/hectare)	2.7	2.5	2.9

Figure 43: Simulated yields under BAU and LDN scenarios (in tonnes/hectare) with error bars



4.1.6 Valuing productivity losses

Continued deforestation of native Cerrado vegetation will compromise land productivity through reduced precipitation levels. To assess the value of lost agricultural production per hectare stemming from such land use changes, the productivity change approach is used, whereby the loss in income is estimated per hectare of soy from 2021 to 2050, as a result of the continued deforestation under the BAU scenario. This is compared to the LDN scenario.

4.1.6.1 Methods

Income from soy cropping

Price information was taken from macrotrends.com,[49] as well as recent crop yields from Iizumi and Sakai (2020). Table 13 summarising the information and the price per bushel has been converted to per hectare terms using 2021 yields. Production costs include both: variable costs, such as seeds, fertilizers, chemicals, fuel, machine repairs and interest on operating capital; and fixed costs, such as land rental rates, ownership costs for capital assets, taxes and insurance costs. Transportation costs range from USD 0.5/bushel in Bahia to USD 2/bushel in Mato Grosso. For simplicity, it is assumed that the average transportation cost is USD 1/bushel. The price of soybeans in 2021 is USD 13/bushel, or USD 477/tonne (macrotrends 2021). The net income at the farmgate[50] is given by equation 5.

$$\text{Net crop income per hectare} = (P - C - TC) \times Q \qquad \text{(eq. 5)}$$

**P is the price per metric tonne received by the farmer at his local warehouse.
**TC is the average transportation cost per tonne for the "presumed drylands" region.
**C refers to production costs per tonne of soy produced.
**Q is soybean yield in tonnes per hectare (2.7 t/ha or 99 bushels/ha).

Accordingly, for 2020/2021, the per hectare net income (or profit) from soy cropping, is in the order of USD 495 per hectare (Table 13).

TABLE 13:
Basic farm budget for a typical soy farmer in the Cerrado

	USD/bushel	USD/tonne	USD/ha for 2021
Price/Revenue	13	477	1 288
Cost of transport	1	37	99
Cost of production	7	257	694
Net income	5	184	495

Sources: M. Cordonnier, personal communication, 2021; Iizumi and Sakai, 2020; macrotrends 2021

Valuation of the loss in agricultural productivity under continued land degradation

The benefit of halting land clearance for soy production may be valued as the avoided loss in agricultural productivity under business-as-usual practices. This is given by the difference in per hectare net incomes under the BAU and LDN scenarios for every year per tonne over the 2021–2050 timeframe, as per equations 6 to 8. The flow of net income is converted into present value terms, using r, the real discount rate of 2 percent, which is adjusted for inflation (trading economics 2020).[51]

$$\text{PV net crop income per hectare}_{\text{BAU}} = \sum_{t=2021}^{2050} \frac{(P - C - TC) \times Q_{BAUt}}{(1+r)^t} \qquad \text{(eq. 6)}$$

$$\text{PV net crop income per hectare}_{\text{LDN}} = \sum_{t=2021}^{2050} \frac{(P - C - TC) \times Q_{LDNt}}{(1+r)^t} \qquad \text{(eq. 7)}$$

$$\text{PV avoided loss in crop income}_{\text{continued BAU}} = \text{PV net income}^{\text{-ha}}{}_{\text{LDN}} - \text{PV net income}^{\text{-ha}}{}_{\text{BAU}} \qquad \text{(eq. 8)}$$

[49] https://www.macrotrends.net/futures/soybean
[50] the price received by the farmer at his local warehouse
[51] It is assumed that the share of output from soy in the "presumed drylands" of the Cerrado within the global market is not sufficiently big to affect world market prices for soybeans through general equilibrium effects. https://tradingeconomics.com/forecasts

4.1.6.2 Results

Over the 2021–2050 timeframe, farmers can expect an annual average net income of USD 409 per hectare in present value (PV) terms under the BAU scenario, associated with continued land clearing, reduced evapotranspiration and rainfall. With no further clearing of native Cerrado vegetation, however, the annual average net income is in the order of USD 523 per hectare in present value terms. Therefore, if LDN is pursued, a 16 percent decline in productivity will be avoided by 2050, as well as an annual net income loss of USD 115 per hectare on average (22 percent). Aggregating over the 2021–2050 timeframe and for all of the Cerrado land that is projected to be lost to soy production, the total benefit of avoided losses to productivity is in the order of USD 105.2 billion. However, as it is not possible to account for the cost differential of acquiring pastureland over native Cerrado land, the overall benefit is likely to be smaller, considering that pastureland is more expensive than native Cerrado vegetation. Estimates in Table 14 assume constant soy prices and agricultural production costs.[52]

TABLE 14:
The value of preserving land productivity under LDN scenario (* On the entire area dedicated to crops, projected to rise from 27.2 million hectares in 2020 to 49.0 million hectares by 2050).

	Per hectare crop revenue – BAU scenario	Per hectare crop revenue – LDN scenario	Benefit of adopting the LDN scenario
Average yield by 2050	2.5 tonnes/hectare	2.9 tonnes/hectare	0.4 tonnes/hectare
Average annual net crop income 2021–2050 (USD/ha/year) in PV terms	USD 409/ha/year	USD 523/ha/year	USD 115/ha/year
PV net crop income 2021–2050 in present value terms (USD/ha)	USD 9 145/ha	USD 11 712/ha	USD 2 570/ha
PV net crop income 2021–2050 for the entire "presumed drylands" of the Cerrado (USD)*	USD 329.7 billion	USD 435.0 billion	USD 105.2 billion

4.1.6.3 Discussion – implications for land use decisions over soy expansion

The question that arises is whether looming production losses and reduced competitivity of soy producers in the "presumed drylands" of the Cerrado are likely to deter present and future investments into further land expansion. On the basis of an interview with an experienced advisor to the soybean industry and the literature, most factors suggest that this is not the case.

First and foremost, soy production is highly profitable. With average farm sizes in the order of 1 000 hectares, farmers may enjoy an annual profit of USD 460 000. Moreover, upfront land investment and clearing costs are minimal in the Cerrado (costing 250 USD/hectare) and hundreds of hectares can be cleared in a single day.

In terms of dry spells and late rains, these climatic risk factors are mitigated by farmers using a mixture of slow, medium and quickly maturing grains. Furthermore, seed varieties are being developed that are more drought resistant, while all major seed companies are currently investing in Brazil, reflecting the situation that industry actors consider there is still high unexploited potential, notably associated with the 'abundant' land available.

Transport costs for soy are higher in Brazil, relative to Argentina and the United States of America, due to poor road conditions and inefficient operations by rail and ports, impeding a smooth flow of grain from farm to port (Fliehr, 2013).[53] This hampers Brazil's competitivity on the global market relative to the United States of America and Argentina. However, continued investments in infrastructure will likely reduce transportation costs in the future and enable producer profitability to improve. Moreover, the expansion of soybean and maize production since the late 2000s along the new agricultural frontier of MATOPIBA,[54] a large part of which

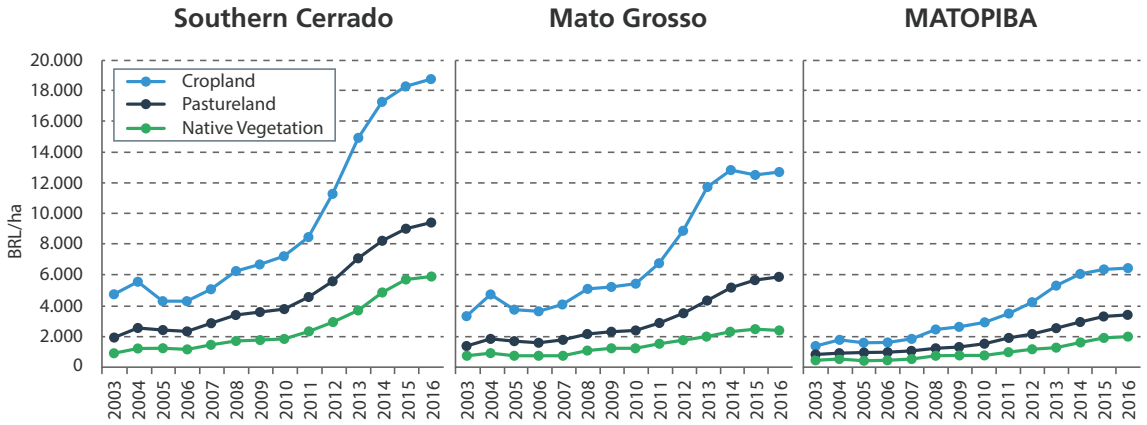
[52] While this is not a realistic assumption, the estimates provide benchmark estimates against which the impact of reduced land productivity can be addressed.

[53] https://www.econstor.eu/handle/10419/78249

[54] an acronym for the northern states of Maranhão, Tocantins, Piauí and Bahia

belongs to "presumed drylands" of the Cerrado, reflects the proximity to transportation and port infrastructure.

Figure 44: Land prices in the Cerrado biome by land use and region (in BRL/hectare)



Source TNC (2019)

Lower costs of land are also major factors encouraging expansion of soy production in "presumed drylands", relative to other soy production areas in Brazil. For example, it is possible to acquire native Cerrado land at USD 200/hectare in Bahia, whereas pastureland in the region of Mato Grosso is priced at USD 1 600/hectare (M. Cordonnier, personal communication, 2021). Comparing three different regions within the Cerrado biome, TNC (2019) also notes that native land is always cheaper than pastureland, for instance, USD 1 200/hectare compared to USD 600[55]/hectare in Mato Grosso state, and USD 1 140/hectare compared to USD 600/hectare in MATOPIBA in 2016, respectively (Figure 44). In all regions, the price gap between cropland, pastureland and native vegetation creates an important incentive to acquire "cheap" native land, develop it and sell it as already-cleared agricultural land.[56] Additionally, for Brazil as a whole, land prices remain low relative to Argentina or the United States of America. As such, land costs are on average USD 41/acre in Brazil, compared with about USD 100/acre in Argentina and USD 110/acre in the United States of America (Meade *et al.*, 2016).

Persistent high soy prices: It takes only two annual record soybean yields across all major soy producing nations to restrain supply and put a downward pressure on international soy prices (M. Cordonnier, personal communication, 2021). With recurrent droughts and heat spells in all major soy production centres (the United States of America, Argentina and Brazil), the supply tends to stay restrained. Combined with growing demand for soy, especially from China, this translates into high prices and high profit margins. According to Cordonnier (personal communication, 2021), *"at these price levels, farmers will expand, expand, expand. Currently we see an annual growth of 3 percent in cropland, and in a few years that may grow to 5 to 6 percent, or even 10 percent."* Brazil has also expanded its market as the Brazilian real (BRL) has experienced a gradual devaluation since 2012 relative to the US dollar, making Brazilian soybeans cheaper on world markets.

Finally, the competitiveness of soy farmers also depends on factors that are a result of policies: macroeconomic policies, such as monetary policies that can have an impact on exchange rates; sector-specific policies, such as import tariffs or export taxes, subsidies, and access to credit; and trade policies or arrangements. Brazil in particular has offered longstanding support to the agricultural sector, for example, by subsidising operating and investment capital credit and providing tax exemptions for both maize and soybean exports (Meade *et al.*, 2016). There are also indirect support mechanisms, including new seed technology developments from the Brazilian Agricultural Research Corporation (EMBRAPA), which have helped to significantly reduce seed costs to farmers.

[55] Using the 2019 exchange rate of BRL 1 = USD 0.3 (2016)

[56] According to TNC (2019), a hypothetical investor who, for example, acquires a 500-hectare parcel of land with native vegetation in the Matopi region and converts 400 hectares to crop production, keeping the minimum required legal reserve of 100 hectares, and then sells the whole area in year five at market conditions, can generate a net present value (NPV) of USD 700 per hectare – i.e. more than USD 350 000 for the entire property using a cost of capital of 7.6 percent.

In the light of all the factors affecting the economics of soy production in "presumed drylands" of the Cerrado, it is unlikely that agro-climatic conditions and the associated decline in profitability under business-as-usual conditions will deter further cropland expansion over native Cerrado vegetation in the years to come. For that to happen, the underlying incentive structures and policies would need to change so that alternative land uses become attractive.

4.1.7 Valuation of the carbon sequestration potential of native Cerrado land

Terrestrial carbon sequestration refers to the capture and long-term storage of atmospheric carbon dioxide (CO_2) by forests, grasslands, wetlands and other terrestrial ecosystems. It is an important ecosystem service that has been a key focus of climate change mitigation efforts (Miteva, Kennedy and Baumgarten, 2014).

The carbon stock of an ecosystem is determined by the environmental conditions and the land use regime of natural and anthropogenic disturbances (Keith *et al.*, 2019). Referred to as the 'upside-down forest' by FAO (2018), it is estimated that the majority of the carbon sequestered in the Cerrado savanna, about 295 tonnes of carbon per hectare (tC/ha), is underground, in the soil and root systems, and many metres deep (FAO, 2018). The conversion of native Cerrado vegetation to soy cropping is therefore likely to lead to significant carbon losses. Conversely, by pursuing land degradation neutrality, significant amounts of carbon emissions could be avoided.

In principle, such emission reductions could be sold on the voluntary carbon market or attract results-based finance through the international REDD+[57] mechanism. The average price for transacted voluntary carbon offsets for forest and land use solutions were in the order of USD 4.3 per tonne of carbon dioxide equivalent (tCO2eq) in 2019 (Donofrio *et al.*, 2020). The REDD+ payment scheme under Norway's International Climate and Forest Initiative (NICFI[58]) initially provided payments of USD 5/tCO2 for the Brazilian Amazon Fund[59] (Miteva, Kennedy and Baumgarten, 2014), but recently decided to double the price it guarantees developing nations in an effort to slow deforestation rates. At USD 10 a tonne, countries could earn USD 5 000 for every hectare of forest they conserve (Doyle, 2020).

These approaches, however, could be criticised on the basis that they bear little relation to the monetary impacts of climate change or the price needed to stay well below 2°C warming. Prices are rather a reflection of the relative supply and demand for carbon credits, or political commitments to emissions reductions and allowances for pollution (Convery and Redmond, 2007). Moreover, transaction costs are not necessarily contemplated, such as costs associated with certification, monitoring and trading, which may be significant (Michaelowa *et al.*, 2003).

It is therefore relevant to estimate the value of carbon emission reductions under the LDN scenario, with respect to the avoided social damage costs of these emissions (Ferraro *et al.*, 2012). This approach allows lower and upper bounds to be provided for the monetary value of carbon emissions under the two land use scenarios.

The social cost of carbon (SCC) attempts to capture the marginal global damage cost of an additional unit of CO_2 emitted into the atmosphere. For SCC estimates, the recommendations produced by the Report of the High-Level Commission on Carbon Prices are used, led by Joseph Stiglitz and Nicholas Stern (CPLC, 2017).[60] The Commission concluded that the explicit carbon-price level consistent with achieving the Paris temperature target and keeping temperature rise below 2 °C is at least USD 40–80/tCO2 in 2020, rising to USD 50–100/tCO2 by 2030, and USD 78–156/tCO2 by 2050, provided that a supportive policy environment is in place (World Bank, 2017). In the calculations set out below, an average between the high- and low-level estimates is used.

4.1.8 Method for valuing avoided emissions

To value the avoided emissions associated with expanding cropland over pastures, instead of over native Cerrado vegetation, the average annual rate of land use conversion is first estimated under each of the scenarios, on the basis of the projections shown in section 4.1.2.3. Second, the

[57] https://redd.unfccc.int/

[58] https://www.nicfi.no/

[59] http://www.amazonfund.gov.br/en/home/

[60] https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59244eed17bffc0ac256cf16/1495551740633/CarbonPricing_Final_May29.pdf

FAO Ex-Ante Carbon-balance Tool (EX-ACT) tool[61] is used to estimate the per hectare carbon emissions associated with converting pasture, forest and native Cerrado land to soy – and the carbon emissions are compared from 2021 to 2050 under the two scenarios. Finally, the monetary benefits of pursuing LDN are valued in terms of avoided social damage costs of carbon or the sale of REDD+ carbon credits, following equations 9 through 12, notably:

For each year t, between 2021 and 2050, the annual GHG emissions in the business-as-usual and land degradation neutrality scenarios are given by:

eq. 9) GHG emissions in $BAU_t = GHG^{-ha}_{pasture \rightarrow soy} \times AC_{pasture \rightarrow soy} + GHG^{-ha}_{cerrado \rightarrow soy} \times AC_{cerrado \rightarrow soy}$

eq. 10) GHG emissions in $LDN_t = GHG^{-ha}_{pasture \rightarrow soy} \times AC_{pasture \rightarrow soy}$

Where GHG are the GHG emissions associated with converting land from one land use category to another, expressed in tCO2eq/year/hectare. AC refers to the area that is converted in year t from that land use type to the other.

For any given year t, the avoided GHG emissions associated with adopting the LDN scenario are given by the difference between the two scenarios (eq. 11).

eq. 11) Avoided GHG $\text{emissions}_{t\ BAU \rightarrow LDN}$ = GHG in BAU_t - GHG in LDN_t

The present value benefit of pursuing LDN instead of the BAU scenario during the 2021–2050 timeframe, is estimated in terms of the avoided social damage costs of additional carbon emissions and in terms of the potential value that farmers can enjoy though the sale of carbon credits, following equation 12:

eq. 12) PV benefit of avoided GHG = $\sum_{t=2021}^{2050} \frac{(P_t/SCC_t \times \text{Annual avoided GHG emissions BAU} \rightarrow \text{LDN})}{(1+r)^t}$

Where SCC is the social cost of carbon for year t (between USD 61.5/tCO2eq and USD 117/tCO2eq) and P is the average price for transacted voluntary carbon offsets in 2019 (USD 4.3/tCO2eq), or certified emission reduction (CER) credits under Norway's REDD+ NICFI scheme (USD 10/tCO2eq), assuming that all of the sequestered carbon can be traded. It is also assumed that carbon credit prices and the social cost of carbon do not change. While that is not likely, the current prices provide us with a useful benchmark of the potential marketable benefits of the avoided GHG emissions.

r is the Brazilian real discount rate of 2 percent. It is also aligned with the social discount rate of 2 percent for medium-run future projects, according to Weitzman (2001).[62]

4.1.8.1 Land cover and carbon pools

Following the estimated land cover changes (mentioned above), native Cerrado land is projected to shrink by 17.6 million hectares (from 59.4 million hectares to 41.8 million hectares by 2050), which corresponds to an annual loss of 606 500 hectares between 2021 and 2050. Forest plantations and pastureland are also predicted to decline, but to a much smaller extent. Of the current 77 million hectares of pastureland, 2.3 million hectares are predicted to be converted to annual crops in the BAU scenario, based on past land use conversion trends.

[61] http://www.fao.org/in-action/epic/ex-act-tool/overview/en/

[62] This is the value for the medium-term future (26–75 years from now). In truly perpetual time frames (i.e. more than 300 years), the social discount rate should be 0 percent (Weitzman, 2001).

At the same time, annual crops are predicted to expand by 23 million hectares during the 2021–2050 timeframe. Cropland expansion will therefore largely come at the expense of Cerrado vegetation in the "presumed drylands" region. However, in the LDN scenario, it is assumed that the expansion of cropland (17.5 million hectares) takes place exclusively over degraded pastureland.

While it is projected that forest zones and plantations will be reduced under the BAU scenario, carbon emission analysis focuses on cropland expansion over Cerrado land versus cropland expansion over pastureland. This is due to the uncertainty as to what is captured as forest in the land cover classifications (e.g. plantations versus natural forests), and how much will be lost to soy versus other land uses.

4.1.8.2 Changes in carbon pools

Changes in the carbon balance are estimated using the FAO EX-ACT tool that enables estimates to be provided of the impacts of agriculture and forestry development projects and programmes on the carbon balance. The carbon balance is defined as the net balance from all greenhouse gases (GHGs) expressed in CO_2 equivalent that were emitted or sequestered due to project implementation as compared to a BAU scenario. EX-ACT is a land-based accounting system, estimating carbon stocks, as well as GHG emissions per unit of land, expressed in $tCO_2eq/ha/year$. The assumptions used in the EX-ACT tool for "presumed drylands" of the Cerrado are shown in Table 15.

TABLE 15:
Assumptions used to parameterise the FAO EX-ACT tool

IPCC climate zone	Tropical moist
Climate	Tropical
Moisture regime	Moist
Global ecological zone	Tropical moist deciduous forest –TAwa[63]
Dominant regional soil type	LAC soils[64]
Implementation phase	1 year
Management practice under soy cultivation	Using no-till and residue integration
Mean above ground biomass harvested in the land use conversion process[65] (from Cerrado or forest plantations to annual crop production)	31 tonnes/hectare

4.1.9 Results on the carbon balance

Using the FAO EX-ACT tool, it was found that expanding soy production over native Cerrado vegetation generates an additional 433.8 CO2eq/year/hectare versus only 11.7 tCO2eq/year/hectare, if the expansion takes place over pastureland (Table 16).

TABLE 16:
Greenhouse gas emissions in tCO2eq from land use conversion scenarios

	Business-as-usual				Land degradation neutrality		
	Carbon emissions. (tCO2eq/ha)	Land converted to soy in 2019–2050 (ha)	Land converted to soy (ha/year)	GHG in tCO2eq/year	Land converted to soy in 2019–2050	Land converted to soy/year	GHG in tCO2eq/year
Cerrado vegetation to soy cropping	433.8	17 590 000	606 552	263 243 448	-	-	
Pastureland to soy cropping	11.7	2 360 000	81 379	976 552	19 950 000	687 931	8 255 172
Total		19 950 000	687 931	264 220 000	19 950 000	687 931	8 255 172
Per hectare				384			12

[63] Global Ecological Zones, South America. http://www.fao.org/3/ad652e/ad652e18.htm

[64] http://www.fao.org/3/j2132s/J2132S22.htm

[65] Following Ribeiro *et al.* (2011), mean aboveground tree biomass (bole, branches and leaves) was estimated to be 62 966 kg/hectare (SE = 14.6 percent) and belowground biomass accounted for 37 501.8 kg/hectare.

In the BAU scenario, it is projected that an average of 606 552 hectares/year of Cerrado vegetation and 81 379 hectares/year of pastureland will be converted to soy cropping. The associated emissions are therefore in the order of 264 million tCO2eq/year (434 tCo2eq × 606 551 ha + 12 tCo2eq × 81 379 ha) or an average of 384 tCO2eq per hectare converted. In the LDN scenario it is assumed that the increase in soy acreage comes at the expense of pastureland only, a land conversion process associated with an additional 12 tCO2eq per hectare (Table 17).

The LDN scenario therefore represents GHG emissions savings in the order of 372 CO2eq/year/ha (384 CO2eq/year/ha – 12 CO2eq/year/ha), with the sparing of 17.5 million hectares of native Cerrado land. This amounts to GHG emissions savings in the order of 256 000 tCO2eq/year or 8.0 billion tCO2eq over the entire 2021–2050 timeframe (Table 18).

TABLE 17:
Avoided GHG emissions from adopting the LDN scenario over the BAU scenario

	tCO2eq 2021–2050	tCO2eq/year	tCO2eq/year/ha
Avoided GHG emissions	8 016 980 000	255 964 828	372

4.1.10 The value of avoided emissions

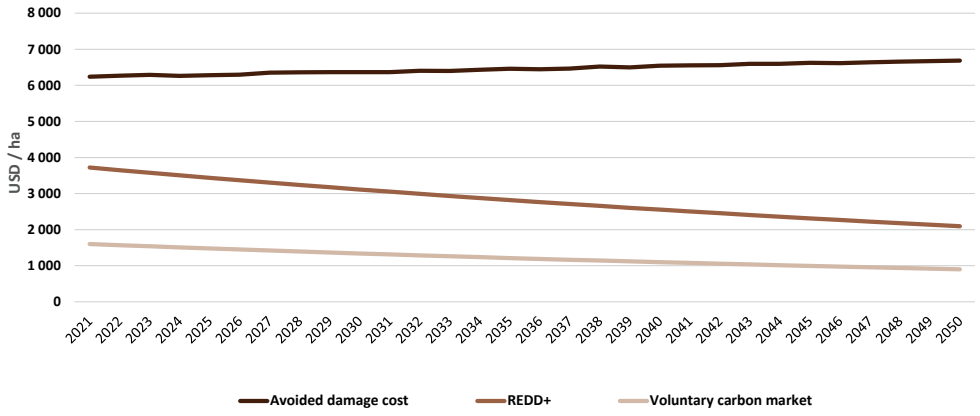
There are significant social costs from the additional carbon emissions associated with the clearing of native Cerrado vegetation following business-as-usual practices between 2021 and 2050. However, climate damage can be mitigated by ensuring that all future cropland expansion within the "presumed drylands" of the Cerrado takes place over degraded pastureland. The average benefit of doing this is in the order of an astounding USD 133.3 billion during the 2021–2050 timeframe. On an annual basis, this is equivalent to a benefit of 8 654 USD/hectare in present value terms.

If these emissions reductions could be sold on the voluntary carbon markets or compensated through REDD+ results-based payments, the benefits are still significant, notably in the order of USD 25.1 to USD 58.6 billion from 2021 to 2050. As such, this is equivalent to an average annual present value benefit of 1 632 to 3 795 USD/hectare of soy that has been grown on converted pastureland instead of native Cerrado vegetation. The per hectare flow of benefits in present value terms are displayed in Figure 45, assuming no changes in the prices of carbon credits (Table 19).

TABLE 18:
Market value of avoided carbon emissions and avoided damage costs from climate change

	Present value benefit 2021–2050 (USD)	Present value benefit per ha 2021–2050 (USD/ha)	Annual present value benefit per ha (USD/ha/year)
Avoided damage cost (using SCC)	133 343 265 642	193 832	8 654
REDD+ payments at USD 10/tonne	58 473 589 813	84 999	3 795
Voluntary carbon market credits	25 143 643 620	36 550	1 632

Figure 45: Avoided damage costs and the value of carbon emissions reductions



Finally, any farmer, foregoing the opportunity to convert native Cerrado vegetation, could earn a one-off payment of USD 1 865/hectare of non-developed land (assuming no transaction costs and that the farmer owns the land). This calculation has to be compared to the forgone profits that can be earned from soy production, which are in the order annually of USD 495/hectare. As shown in Table 19, payment for emissions reductions through a REDD+ scheme at USD 10/tonne and within the perspective of a 10-year timeframe would generate earnings of USD 4 338/hectare against USD 4 213/hectare from the cultivation of soy in present value terms, making it marginally worthwhile. If farmers took a 30-year perspective and had a low personal discount rate, soy cultivation is more profitable. From both a 10-year and 30-year perspective, soy cultivation is more profitable than the sale of carbon credits in the voluntary carbon market.

TABLE 19:
Benefits from forest carbon payments in 2021 and forgone earnings from soy cultivation (*discounted into present value terms at the real interest rate of 2 percent)

	Avoided carbon emissions	Price per carbon credit	One-off sale of carbon credits	Forgone earnings from soy cultivation (10 years)*	Forgone earnings from soy cultivation (30 years)*
REDD+ payments at USD 10/tonne	433.8 tCO2eq/ha	USD 10/tCO2eq	USD 4 338/ha	USD 4 213/ha	USD 9 144/ha
Voluntary carbon market credits	433.8 tCO2eq/ha	USD 4.3/ tCO2eq	USD 1 865/ha	under BAU yields	under BAU yields

4.1.11 Summary of valuation results and limitations

4.1.11.1 Results summary

Summarizing the results from the last two sections, there are significant benefits associated with expanding soy production over degraded pastureland, instead of converting native Cerrado vegetation. This implies that some 17.6 million hectares of native Cerrado land can be spared (606 500 hectares per year) as shown in Table 21. The average present value (PV) benefit in terms of preserving land productivity and the bottom line for farmers is USD 117/hectare (USD 536/hectare in LDN minus USD 419/hectare under BAU), resulting in some USD 105.2 billion benefits for the whole of the "presumed drylands" area within the Cerrado from 2021 to 2050. To understand the full picture, however, further research is required to account for the additional costs associated with purchasing pastureland instead of native Cerrado land. The potential benefit from the sale of carbon credits between 2021 and 2050 is in the order of USD 25.1–58.5 billion (low-end, voluntary carbon market, and upper-end REDD+ payments), while the climate-related cost associated with

continued clearing of native Cerrado land (USD 133 billion) amounts to an astounding one-third of the value of the projected income from soy production under BAU practices (USD 329.7 billion).

TABLE 20:
Benefits from the sale of carbon credits in 2021 and forgone earnings from soy cultivation (*across the entire area dedicated to crops within the "presumed drylands" areas, projected to rise from 27.2 million hectares in 2021 to 49 million hectares by 2050; **on 17.6 million hectares of native Cerrado land projected to be lost for soy cropping from 2021 to 2050)

Monetary valuation of soy expansion scenarios		Per hectare per year	Present value benefit in Cerrado's "presumed drylands" for 2021–2050,
BAU – soy expansion through conversion of native Cerrado vegetation	Net income from soy production in PV terms (2021–2050)*	USD 409/ha/year	USD 329.7 billion*
LDN – soy expansion on degraded pastureland only	Net income from soy production in PV terms (2021–2050)*	USD 523/ha/year	USD 435.0 billion*
Soy production Net-benefit: BAU to LDN scenario	Entire "presumed drylands" of the Cerrado per year	USD 117/ha/year	USD 105.2 billion*
Carbon sequestration	PV of marketable carbon credits**	USD 1 632–3 795/ha/year	USD 25.1–58.5 billion**
Net-benefit: BAU to LDN scenario	PV avoided damage costs from carbon emissions**	USD 8 654/ha/year	USD 133.3 billion**

4.1.11.2 Limitations and recommendations: the case for assessing the full range of costs and benefits associated with BAU and LDN scenarios in future assessments

The above analysis shows that there are economic costs (in terms of damage costs from carbon emissions and reduced land productivity by soy producers) associated with continued deforestation of native Cerrado vegetation. However, this is only a partial analysis of the many knock-on effects of land degradation.

Other sectors and stakeholders are also likely to be impacted by lower precipitation levels, such as the forestry sector or peasant and traditional communities dependent on pastureland and farmland for subsistence cropping. In particular, the overall availability of water is likely to be further compromised. Currently, there is already evidence that agribusiness has impacted the water balance, with streams running dry in the wet season (Prager and Milhorance, 2018; Spera *et al.*, 2016). However, the absolute consequences of large-scale landscape modification and their impacts on water balance remain unknown (Oliveira *et al.*, 2014), and therefore require further research.

Lower precipitation levels may also change the timing of the onset of the dry and wet seasons, and lead to longer dry spells within the wet season, which was previously not common in the Cerrado (Prager and Milhorance, 2018). Furthermore, such changes are likely to impact the returns on agriculture, for instance, by decreasing the ability of farmers to double crop during the wet season (Dickie *et al.*, 2016). On the other hand, new and more drought-tolerant seed technologies may counteract these tendencies.

At the societal level, there are other ecosystem services and functions that are impacted by continued clearing of the native Cerrado vegetation, such as reduced biodiversity and wilderness, recreational opportunities and ecotourism, water yields, erosion control and wild forest produce.

Lastly, the feasibility of expanding cropland over pastures also hinges on the possibility of improving the productivity of remaining pastureland (for instance, through agrosilvopastoral systems), in order to not compromise livestock production and food security in the long run. It is therefore essential that the economic feasibility of sustainable pasture management is assessed as part of such an analysis.

These arguments highlight the need to account for the full set of ecosystem services that are

affected by any serious attempt to avoid further land degradation of "presumed drylands" of the Cerrado through the lens of expanding cropland over pastureland. As such, this is an area for future research. Table 21 summarises the production systems and ecosystem services, and the hypothesized impacts (positive or negative) that a comprehensive cost–benefit analysis should seek to assess.

TABLE 21:
Ecosystem services which remain to be valued as part of a comprehensive cost–benefit analysis

Full range of production systems and ecosystem services impacted by the two land use scenarios and expected direction of the impact	BAU	LDN
Productivity of soy farming	-	+
Carbon sequestration	-	+
Productivity of smallholder food cropping systems	-	+
Productivity of pastureland	-	?
Productivity of sustainably intensified pastureland, e.g. agrosilvopastoral systems	?	?
Wild forest produce	-	+
Biodiversity, wilderness value and ecotourism	-	+
Water yield, groundwater infiltration and erosion control	-	+

4.1.12 Pathways to sustainable soy production

There is no sign that global demand for soybeans will decline. Indeed, 2020 was a record-breaking year for Brazilian soy exports, while soy production is associated with heightened risk of both legal and illegal deforestation, with links in Brazilian supply chains and investments. This situation has sparked concern in the European Union and threatens restricting access to financial markets and undermining the trade deal being finalized with the Mercosur group[66] of Latin American countries (Sharma, 2020).[67] Nevertheless, the Chinese market has not shown the same level of concern around deforestation linkages and risks, positioning China as a key leakage market for unsustainable soybean exports with Brazil and China strengthening trading ties. In 2020, 72 percent of Brazilian soybean exports were destined for China, up from 15 percent in 2000 (farmlandgrab.org, 2020).

As stipulated in the LDN scenario, however, it is possible to stop the conversion of native Cerrado habitat, by focusing on converting low-productivity pastureland into cropland (TNC, 2019; Strassburg *et al.*, 2014). The acquisition of pastureland for soy and its transformation to crop production is already prevalent if one considers the Cerrado as a whole, since 61 percent of expansion across the biome has historically occurred on pastureland (TNC, 2019). In the MATOPIBA region, conversely, 80 percent of soy expansion since 2000 has occurred over native vegetation (Soterroni *et al.*, 2019). In the light of these trends, it is necessary to consider what can be done to incentivise the expansion of cropland over pastureland and the sustainable intensification of current output levels.

4.1.12.1 Incentive-based mechanisms

i. Carbon markets

From the perspective of landowners in "presumed drylands" of the Cerrado, carbon stocks or hydrological ecosystem services only have concrete value if they can receive compensation or be rewarded for maintaining them. In the case of the Cerrado, it has been shown in section 4.1.7 that avoided emissions are in the order of 372 tCO2eq for every hectare of native Cerrado vegetation that is preserved. Under REDD+, landowners could in theory earn USD 3 720/hectare of preserved forest within a 10-year timeframe. However, as shown in section 4.1.6, neither this valuation nor the prices on the voluntary carbon market are enough to overcome the forgone benefits from not clearing and cropping on native Cerrado land (which are in the order annually of USD 495/hectare).

ii. Lower bureaucracy, financial instruments and phasing out of distortionary policies

It has also been argued that those farmers who are embracing sustainability should face lower bureaucracy and transaction costs. According to Hillsdon (2018), the CEO of Denofa, a Norwegian company which sources certified deforestation-free soy from Brazil "it is important to remove the

[66] https://www.mercosur.int/en/
[67] https://www.iatp.org/documents/climate-land-use-change-and-eu-mercosur-agreement-accelerating-tipping-points

cost of taking responsibility, by easing the burden for those farmers that are doing the right thing and pushing the burden over to those farmers and areas that are not."

In addition to payments for environmental services (PES) and lower bureaucracy, there are financial instruments which can be used to incentivise and improve the returns of renting or buying pasture for soy crop expansion. They include the possibility of using existing official credit lines for low-carbon agriculture (e.g. BNDES ABC Agri Credit[68]), which currently finances sustainable cattle ranching and crop-livestock integration, but not the conversion of pastureland to soy. Low-cost credit would increase the rate of return on expanding over pastureland, relative to native vegetation in any region of the Cerrado. Other options to support pasture acquisition and conversion are discussed in detail in TNC (2019). As such, these options would all need to be accompanied with actions that can support cattle ranching intensification in order to free up low productivity pastureland.

In general, soy and maize producers in Brazil have enjoyed long-standing direct or indirect government support, for example, in the form of price floors, credit support or research that has helped lower the cost of seeds (Meade *et al*., 2016). These distortionary policies would need to be phased out or coupled with criteria requiring compliance with deforestation-free standards, in order to remove economic incentives for further clearing of native vegetation.

iii Legal instruments and public-private policy mixes

Brazil's Forest Code requires the conservation of 80 percent native vegetation on private lands in the Amazon biome, but only 20 percent in the Cerrado (35 percent of the Cerrado is located in the Legal Amazon). However, the enforcement of the Forest Code has been poor, and in recent years the Brazilian government has abandoned command-and-control policies to halt illegal deforestation and has been removing environmental protections (Rochedo *et al*., 2018).

For these reasons, the Forest Code is not sufficient to protect the Cerrado, and private sector commitments may be necessary as well. In the Amazon, for example, Nepstad *et al*. (2014) argue that regulatory measures together with zero-deforestation commitments represented by the Amazon Soy Moratorium (ASM)[69] were what helped reduce deforestation. For example, according to Gibbs *et al*. (2016), an estimated 65 percent of the soy farms surveyed in the Amazon's Mato Grosso region do not comply with the Forest Code, but do comply with the Amazon Soy Moratorium. Under the ASM, 90 percent of companies in the Brazilian soy market agreed not to purchase soy grown on land deforested after 2006 within the Amazon biome. It is the first major voluntary zero-deforestation agreement that has been achieved in the tropics. However, the ASM is not a concern for agribusiness in the Cerrado: all soy produced there can be marketed with the ASM claim that it caused "zero deforestation in the productive chain", even if it was cultivated on recently cleared land (Branford and Torres, 2017). As such, the ASM should be expanded to the Cerrado. In this case, a public-private policy mix, combining rigorous enforcement of the Forest Code and full compliance with the ASM's expansion to include the Cerrado, could help preserve the Cerrado (Soterroni *et al*., 2019).

In general, since the mid-2000s, there has been a growing number of initiatives to encourage sustainable production and sourcing of soy. This is reflected in new deforestation-free soy targets by retailers, food manufacturers, and traders in their supply chains, as well as multistakeholder soy roundtable initiatives established in several European countries. Examples include the Responsible Soy Declaration,[70] the Collaborative Soy Initiative,[71] the Sustainable Soy Trade Platform (SSTP[72]), and the Amsterdam Declaration on Deforestation in the Amsterdam Declarations Partnership (ADP[73]), the Soft Commodities Forum (SCF[74]) and the Cerrado Manifesto.[75] The latter calls on the private sector to take immediate action to protect the Cerrado and over 60 companies have

[68] https://www.blendedfinance.earth/sustainability-linked-debt/2020/11/13/bndes-abc-agri-credit

[69] The ASM banned direct conversion of Amazon forests to soy after 2006.

[70] https://www.forfarmersgroup.eu/en/media/news/forfarmers-supports-responsible-soy-declaration.aspx https://responsiblesoy.org/rtrs-define-su-posicion-como-la-plataforma-global-de-soja-sustentable-y-propone-una-agenda-mas-holistica-que-trascienda-la-deforestacion-cero?lang=en

[71] https://thecollaborativesoyinitiative.info/

[72] https://www.solidaridadnetwork.org/news/first-steps-towards-responsible-soy-sourcing-guidelines-for-china/

[73] https://ad-partnership.org/

[74] https://www.wbcsd.org/Programs/Food-and-Nature/Food-Land-Use/Soft-Commodities-Forum

[75] https://cerradostatement.fairr.org/

joined to date. For a comprehensive review of supply and demand-led private sector initiatives, the reader is referred to IDH (2020).[76]

Despite these mounting number of initiatives, the Brazilian Space Agency reported a 12-year high deforestation surge for 2020 (BBC, 2020). According to Taylor and Streck (2018), unfortunately, many companies have failed to deliver or to set deadlines. Moreover, due to low domestic supplies and the depreciation of the Brazilian real (BRL) relative to the US dollar (USD), soybean prices reached nominal records in 2020. Currency rates in 2020 also lowered the costs of agricultural inputs, such as fertilizers and agrochemicals. The dual impact of higher soy prices and lower input costs have resulted in higher profits, leading to expansion in cultivated soybean area (Colossi and Schnitkey, 2020). As argued in section 4.1.6.3, this situation is likely to persist and continue to make soy cropping highly profitable in the Cerrado. The COVID-19 pandemic has also complicated the situation, as it has reduced the capacity of authorities to act and control forests and grasslands for early signs of wildfires (BBC, 2020).

4.1.13 Conclusions and recommendations

The continued clearing of native Cerrado vegetation involves significant losses to society, notably from climate-related damage costs that are in the order of USD 133 billion by 2050, and losses to agricultural productivity estimated at USD 105 billion by 2050. As such, even without accounting for the full set of ecosystem services currently provided by the Cerrado forest, the analysis clearly shows an example of a market failure, in that the ecosystem service values of native Cerrado land, such as its role in regulating hydrological and carbon cycles and micro-climate stability, are not reflected in prevailing market prices for the land (with Cerrado land being cheaper than pastureland and cropland).

While current forest carbon finance schemes are not of sufficient amplitude to allow for compensating landowners from forgone profits of soy cropping, other potential market-based instruments and opportunities can contribute to internalising ecosystem service benefits. These include PES schemes for water and the extension of the use of existing official low-interest credit lines for low-carbon agriculture (TNC, 2019). Fiscal policy reforms (e.g. adjusting land ownership costs, using environmental commodity taxation or agricultural subsidies to reward sustainable management of forests and farmland) could also be a powerful tool to help reduce deforestation and promote sustainable land management, as highlighted in a recent report by Climate Investment Funds- Forest Investment Program and the World Bank (World Bank, 2021).[77]

Similarly, reforms of agricultural support policies and regulatory incentives which directly or indirectly encourage the expansion of agricultural land over native vegetation should be undertaken. For example, while Brazil's Forest Code requires the conservation of 80 percent of native vegetation on private lands in the Amazon biome, only 20 percent is required in the Cerrado. Moreover, the enforcement of the Forest Code has been poor in recent years (Rochedo *et al*., 2018).

There are deepening concerns over the loss of species habitat and biodiversity, and heightened awareness about the long-term ecosystem and financial risks associated with deforestation. Consumers, NGOs and investors are therefore urging food companies and financial institutions to devote more resources to addressing deforestation in their supply chains (Clancy, 2021). Unfortunately, among the companies that have made commitments to end deforestation, many have failed to deliver or to set deadlines (Clancy, 2021; Taylor and Streck, 2018).

Tighter legislation, economic instruments and incentives, as well as continued consumer pressure, will be necessary to tilt the balance in favour of halting deforestation and restoring degraded pastureland within "presumed drylands" of the Cerrado.

The feasibility of expanding cropland over degraded pastureland in the LDN scenario also hinges on the possibility of improving the productivity of the remaining pastureland (e.g. through agrosilvopastoral systems), in order not to compromise livestock production and food security in the long term.

The costs and benefits of expanding cropland onto degraded pastureland need to be assessed,

[76] https://www.idhsustainabletrade.com/uploaded/2020/05/IDH-European-Soy-Monitor-v2.pdf

[77] https://www.climateinvestmentfunds.org/news/new-report-shows-how-fiscal-reforms-can-positively-influence-forest-conservation-and-ecosystem

as well as the additional costs of expanding soy production exclusively onto degraded pastures as opposed to native Cerrado vegetation, as part of a comprehensive cost–benefit analysis for the case of halting land degradation within the Cerrado.

At the societal level, there are other ecosystem services and production systems impacted by the continued clearing of native Cerrado vegetation, such as biodiversity, recreational opportunities, water yields, erosion control, wild forest products and food cropping. The value of these impacts should be accounted for in future research to comprehensively assess the benefits and costs associated with halting deforestation within "presumed drylands" of the Cerrado. That said, the study presented here is the first of its kind to estimate the production losses associated with changing micro-climates due to land degradation in "presumed drylands" of the Cerrado. As such, it is a significant contribution to the existing literature and confirms the need to address land degradation and current land management practices within presumed dryland areas of the Cerrado.

5. Valuing the case for regenerating tree cover within croplands of the Miombo–Mopane region

5.1 SETTING THE SCENE

Forest products are the backbone of rural household economies in sub-Saharan Africa, and also within the "presumed drylands" of Miombo–Mopane woodlands. Timber and non-timber forest products (NTFPs) serve as energy sources, foodstuffs, medicinal products, construction materials, as well as equipment for agricultural activities (Sheil and Wunder, 2002; Vedeld *et al.*, 2004; Syampungani *et al.*, 2009). For instance, fruit trees provide vital nutrients that may otherwise be scarce and wild foods help contribute to the region's food security. It has also been shown that tree and shrub forage also provides important nutrients to livestock in Malawi, the United Republic of Tanzania and Zimbabwe (Chakeredza *et al.*, 2007). In terms of fuel for cooking, wood and charcoal remain the main energy sources used by rural and urban households. In Angola, Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe, biomass accounts for 60 to 90 percent of energy consumption (Gumbo *et al.*, 2018).

Energy consumption represents a significant driver of forest and canopy-cover loss. Tree densities within croplands have been declining (section 3.2) and the Miombo–Mopane woodlands as a whole are threatened by land use changes and increasing competition for arable land, which have intensified over the last 50 years (Gumbo *et al.*, 2018). Moreover, poorly implemented shifting cultivation practices and uncontrolled fires are common in the region (Tarimo *et al.*, 2015). The clearing of vegetation for cultivation and the resulting loss of woodland cover negatively impact the hydrology and ecological functions and has cascading effects on biodiversity (Timberlake and Chidumayo, 2011). The harvesting of trees for charcoal production furthermore affects plant litter inputs to soils and results in changes in the soil environments that modify the functioning and composition of soil microbial communities (Lisboa *et al.*, 2020). Considering that the Miombo–Mopane woodlands are characterised by an edaphic environment of typically leached, shallow and impoverished soils (Timberlake and Chidumayo, 2011), this is particularly problematic for long-term land productivity.

The regeneration of on-farm tree cover can help counter these tendencies and alleviate pressure from fuelwood harvesting within woodlands. With reference to Katavi and Tabora regions in the United Republic of Tanzania, uses of on-farm forest resources include fuelwood for charcoal production, in addition to food and honey production, or for construction materials or medicines (FAO and GEF, 2020).

With respect to on-farm tree cover, the latest Earth observations (section 5.4 below), however, show that there has been a substantial decline in on-farm tree cover, of 34 percent in the United Republic of Tanzania and 36 percent in Angola between 2000 and 2019, respectively (see Table 23). The aim of the current assessment is to understand the implications for farmland productivity from this loss. Substantial evidence has highlighted the importance of trees, not just in terms of provisioning ecosystem services as already mentioned, but many other benefits that help maintain or improve land productivity. The purpose here is to analyse whether such positive synergies hold for farmland within "presumed drylands" of the Miombo–Mopane woodlands, and in which case, can they provide a guide to how the current pace of land degradation should be halted and the value of doing so?

To address these questions in this study, the existing literature is first considered on crop-yield synergies. The methodology used to analyse tree canopy cover and crop yield relationships is then explained. Subsequently, a closer look is taken at tree cover within "presumed drylands" of

Mozambique, the United Republic of Tanzania, Angola, Zambia and Zimbabwe, and with respect to one country, notably the United Republic of Tanzania, an analysis is carried out of how tree canopy cover changes have impacted land productivity. On the basis of this, the value of regenerating tree cover is assessed under two scenarios in "presumed drylands" of the United Republic of Tanzania: LDN1, stipulating a stabilisation of current tree densities within croplands; and LDN2, stipulating an increase in canopy cover to year 2000 levels. The LDN scenarios are compared relative to the business-as-usual trajectory (the BAU scenario), which assumes continuation of the current pace of on-farm tree cover loss. Finally, recommendations are made for future research and policy actions.

5.2 EXISTING EVIDENCE TO SUPPORT CANOPY COVER IN CROPLAND AND LAND DEGRADATION NEUTRALITY

An increasing body of evidence is showing that agroforestry involving deliberate planting of trees or farmer-managed natural regeneration (FMNR) are effective strategies for improving land productivity. Tree shade can significantly reduce temperature and soil evaporation, leading to higher soil moisture with major benefits for crop performance (Lott, Ong and Black, 2009; Ludwig *et al*., 2004). Trees also contribute to soil carbon, improve soil humidity and nitrogen fixation, which enhances soil structure and increases the ability of crops to take up nutrients (Sidibé, Myint and Westerberg, 2014; Bayala *et al*., 2012). As a result, these processes lead to higher crop yields. In Niger, Mali and Burkina Faso, for example, the presence of mature fertilizer trees explained 15–30 percent alone of cereal yields (Place *et al*., 2016).

In Niger, an estimated five million hectares have been regreened via FMNR. Bayala *et al*. (2012) found that when tree cover is low, the production of cereals is low (about 200 kg/hectare). As tree density increases, yields can reach 300 kg/hectare. The highest yields usually occur when FMNR has been used for several years,[78] with yield increases being attributed in large part to enhanced soil carbon because it helps improve soil structure (Watson, 2018).

A series of studies by the Economics of Land Degradation Initiative[79] have also assessed the contribution of agroforestry and FMNR practices to crop yields. In particular, in the Upper West Region of Ghana, Westerberg *et al*. (2019) showed that farmers can increase revenue from crop harvests by an estimated 83 percent within five years through the uptake of FMNR and crop rotation. As tree density and maturity increases, so does the crop yield.

Using the FAO aquacrop model,[80] Sidibé, Myint and Westerburg (2014) show that the additional soil moisture alone generated by *Faidherbia albida* fertilizer trees, in millet cropping schemes in the Mopti region of Mali, can increase yields by 24 kg/hectare, corresponding to a 9 percent increase in yields. Furthermore, nitrogen fixation by *F. albida* enables approximately 1.32 kg of nitrogen per hectare to be fixed, worth an average of USD 16.7/hectare in avoided costs had nitrogen to be replaced with inorganic fertilizers. When accounting for the contribution of firewood, fodder, increased soil moisture and nitrogen fixation, the results suggest that farmers enjoy USD 5.2 benefits for every dollar invested in the system.

Within the Miombo–Mopane region, in Malawi, Coulibaly *et al*. (2017) found that the use of fertilizer trees by smallholder farmers increased the value of food crops by 35 percent, which was particularly vital for small landholders. Smallholders participating in an FAO climate-smart agriculture (CSA) programme – in which the use of fertilizer trees was the most important component – saw maize yields increase by 20 percent (Amadu, Miller and McNamara, 2020). Similar findings from Malawi have been demonstrated by Quinion *et al*. (2010), while supported by agroforestry interventions in fifty-seven developing countries in Pretty *et al*. (2006).

Despite the overwhelming evidence for the benefits provided by agroforestry when combined with agriculture, mainstream agricultural programmes tend to only focus narrowly on heavy mechanisation (requiring as few obstacles as possible in the farmland) and using inorganic inputs. In the United Republic of Tanzania, for example, the agricultural programmes[81] which are aimed to increase maize productivity do so through the provision of subsidies on inputs such as fertilizers

[78] https://news.mongabay.com/2018/06/farmer-managed-natural-regeneration-the-fastest-way-to-restore-trees-to-degraded-landscapes/

[79] https://www.eld-initiative.org/en/who-we-are/about-eld/

[80] http://www.fao.org/aquacrop/en/

[81] For example, "Kilimo Kwanza" (agriculture first) and the Agricultural Sector Development Programme (ASDP1 & 2).

and pesticides in the major maize growing areas (Ruvuma, Mbeya, Iringa and Rukwa), as well as through fixed price floors above the market price. To absorb any surplus, the Government of the United Republic of Tanzania establishes strategic grain reserves under the National Food Reserve Agency (NFRA),[82] which buys maize from farmers to guarantee national food security (USDA Foreign Agricultural Service, 2019).

Empirical data and literature, however, suggest that there is also scope for viewing trees as a strategic input into the production of maize and as a means to enhance food security and land productivity. This is consistent with Tanzania's pledge to become land degradation neutral. The voluntary targets of the United Republic of Tanzania's LDN strategy developed in 2018 include: the improvement of land productivity of 8.5 million hectares of cropland by 2025; increasing soil organic carbon in cropland to 54.5 tonnes/hectare by 2030; reducing soil erosion on cropland; and targets to prevent the decline in land productivity of 2.6 million hectares of forests, the restoration of 11 million hectares of forests and increasing land productivity of 1.7 million hectares of shrub and grassland by 2030.

5.3 STUDY METHOD AND DESIGN

The above literature shows that trees contribute to enhancing land productivity through multiple mechanisms, from increasing soil moisture and fixing nitrogen to reducing soil erosion and improving soil organic carbon levels. In the absence of conducting field studies for this assessment, it was not possible to analyse the contribution of these various factors to crop yields or to control for other influencing parameters such as agronomic and meteorological conditions, tree species composition and the practices adopted by farmers[83] (kind and level of farm inputs used and when applied). Therefore, global data sets and satellite imagery were relied on, enabling information on crop yields to be overlaid with canopy cover for "presumed drylands" only, as explained below.

Using this method, the role of climate in explaining crop yields has been indirectly controlled for, as the focus is on presumed dryland areas with the same aridity index. In addition to precipitation levels, the impact from inputs such as fertilizers or farm labour is also likely to be limited. This is because fertilizer application rates or variations in labour supply may be viewed as random and attributable to factors that cannot be observed, such as the presence of vendors, or the location of farms – as opposed to being correlated with canopy cover. Under such circumstances, there is no hidden impact of fertilizers biasing the statistical analysis of the relationship between crop yields and canopy cover.

In term of crops, the analysis carried out is restricted to maize yields, as it is the main staple crop in the United Republic of Tanzania and across the Miombo–Mopane woodlands overall. Maize occupies about 45 percent of the cultivated area in the United Republic of Tanzania according to FEWS NET (2020), and 22 percent of the cropland within "presumed drylands" of the United Republic of Tanzania (derived from the corresponding authors' own calculation (see Figure 46 for the spatial distribution of crop yields within the "presumed drylands" biome). Approximately 3.5 million subsistence households in the country grow maize as the main staple.[84]

5.3.1 Steps to measure canopy cover and cropland relationships and the economic value

To investigate the empirical relation between maize yield and the amount of tree canopy cover, the following steps were undertaken:

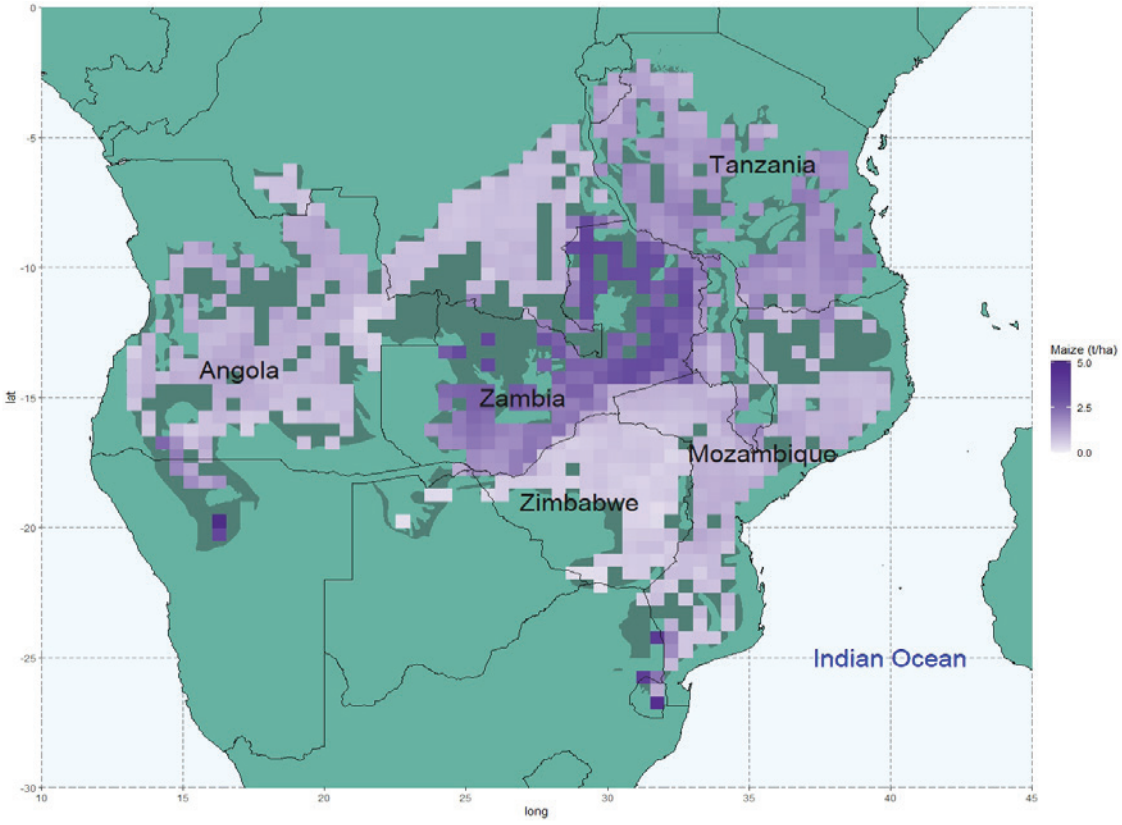
- Crop yields were extracted in tonnes/hectare from Iizumi and Sakai (2020). These were subsequently averaged over a 5-year period in order to smooth inter-annual variations and represent expected typical annual yields at 50 km resolution (Figure 46).

[82] http://www.fao.org/in-action/mafap/resources/detail/en/c/1170237/

[83] On the one hand because field and household surveys were not possible within the timeframe for this study and in the context of the COVID-19 crisis, on the other hand due to the absence of global geospatial data with sufficiently high resolution. For example, while the use of fertilizers might vary in a given country, currently homogeneous spatial data are not available across the Miombo–Mopane region that would allow the yield variability associated with this factor to be inferred.

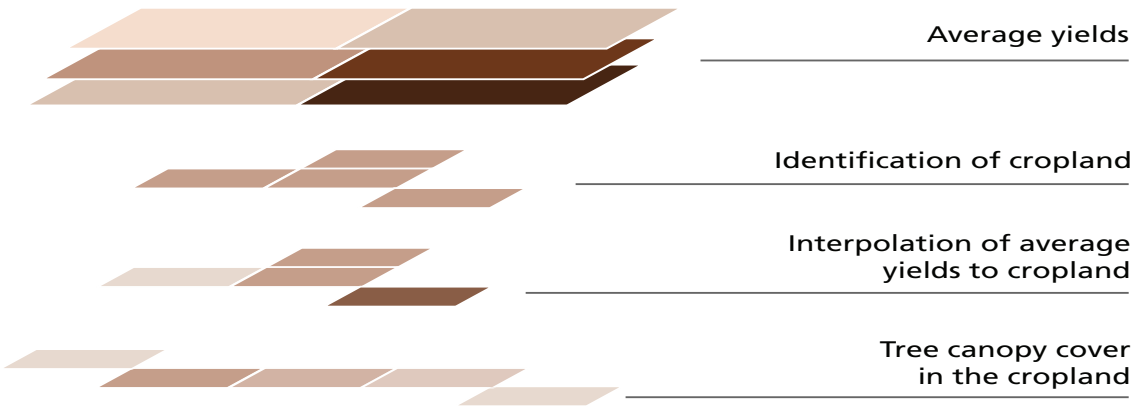
[84] https://www.selinawamucii.com/produce/cereals/tanzania-maize/

Figure 46: Spatial distribution of 2016 yields for maize within the Miombo–Mopane woodlands region
Source : authors



- Second, land cover classifications from Buchhorn *et al.* (2020) were used to identify and extract cropland areas with maize at a 100-metre resolution for each country within the "presumed drylands" biome.
- Third, for each country under consideration, averaged 2010–2015 crop yields were linearly interpolated to match the land cover resolution.
- Fourth, each cropland pixel was overlaid with 2019 data on canopy coverage in order to extract the average percentage of tree canopy cover within the cropland for year 2000 and year 2019. Only trees higher than 5 metres were accounted for.
- Finally, a linear regression analysis was run of the interpolated pixels of cropland yields for maize (the dependent variable) against the corresponding average tree canopy cover (Figure 47).

Figure 47: Steps in assessing canopy cover and cropland relationships


Average yields
Identification of cropland
Interpolation of average yields to cropland
Tree canopy cover in the cropland

5.3.2 Economic valuation of canopy cover and crop yield relationships

The benefits of the canopy cover are valued using the productivity change approach. It is applied in cases where products or ecosystem services (in this case, trees in farmland) are used, along with other inputs, to produce a marketed good (maize), while assuming that other inputs to production are held constant. In this way, the economic benefits of improved land productivity can be measured through increased revenues from greater agricultural output. The additional revenues are estimated as the difference in crop yields with and without a given level of canopy cover, multiplied by the unit price of the crop, less the costs of production (Barbier, 1996) over the timeframe under consideration as per Equation 1.

Therefore, the present value (PV) benefits to the United Republic of Tanzanian society of increasing canopy cover associated with either of the LDN scenarios, are given by Equation 1:

$$Present\ Value\ benefits_{BAU \rightarrow LDN} = \sum_{t=2021}^{2050} \frac{(maize\ yield_{BAU} - maize\ yield_{LDN}) \times P}{(1+r)^t} \quad \text{(eq. 1)}$$

Where:
P is the most recent free-on-board (FOB) wholesale price for maize;
r is the discount rate; and
t is the year under consideration between 2021 and 2050.

The annual value of the year-to-year benefits (i.e. the annuity value) from the LDN scenarios is calculated according to Equation 2. In this case, it is the annual present value of the future flow of crop revenue at the specified interest rate.

$$Annuity_{BAU \rightarrow LDN} = \frac{r \times PV}{1-(1+r)^t} \quad \text{(eq. 2)}$$

The net present value (NPV) of implementing either of the LDN scenarios, is given by Equation 3, and accounts for the additional costs of regenerating the canopy cover over the timeframe evaluated. In the absence of field work, data collection and pilot testing, basic benchmark estimates from the literature are used.

$$Net\ Present\ Value_{BAU \rightarrow LDN} = \sum_{t=2021}^{2050} \frac{(maize\ yield_{BAU,t} - maize\ yield_{LDN,t}) \times P - Cost_{LDN,t}}{(1+r)^t} \quad \text{(eq. 3)}$$

5.3.2.1 Prices

Agricultural policies and trade measures are frequently put in place around maize in order to ensure food security in the United Republic of Tanzania (USDA Foreign Agricultural Service, 2019). Taxes and subsidies, however, should be excluded in economic valuations as they represent transfers between parties in the economy and are not resource costs. Therefore, national prices[85] are incorrect measures of the societal economic benefits when such distortions exist. For most traded goods and services, the appropriate shadow price[86] is the world market price at the border, the so-called free on board price (FOB).[87] International maize prices currently hover around their highest in 10 years (see e.g. online FAO Food Price Monitoring and Analysis [88]), amid concerns over tightening global supplies due to reduced output and stronger demand from importers led by China, as well as population growth (FAO CCP, 2021). With no sight of slackening demand, or significant increases in supply, the most recent FOB price is used for maize (USD 270/tonne), as a benchmark indicator of present and future maize prices.

5.3.2.2 The discount rate

The selection of the discount rate should be based on the opportunity cost of drawing funds for the regeneration of the canopy cover. Accordingly, the cost of investing Tanzanian Shillings is the value that each dollar would have produced in an alternative use (an average of 12 percent return on investment). Therefore, in order for the regeneration to be worthwhile at the societal level, the

[85] The 5-year average nominal wholesale price of maize is in the order of approximate TZS 650/kg in Dar es Salaam (https://fews.net/sites/default/files/documents/reports/PB_TZ_202105.pdf).
[86] https://marketbusinessnews.com/financial-glossary/shadow-price-definition-meaning/
[87] FOB is the world market price at the border.
[88] http://www.fao.org/giews/food-prices/international-prices/en/

invested capital should grow more than if the 'shilling' was invested elsewhere, for example, in a bank account or another land management project. For this purpose, the real interest rate of 12 percent is used for the United Republic of Tanzania.[89] Assuming that reforestation is covered in part or entirely by grants, there are no opportunity costs to farmers of such funds, as they would not be able to invest the funds elsewhere. However, some effort remains at the farmers' own expense. To reflect this situation and allow for a sensitivity analysis, benefits and costs are also discounted using an interest rate of 2 percent.

5.4 RESULTS AND KEY FINDINGS

5.4.1 Significant positive relationship between tree canopy cover and crop yields

Figure 48 shows scatterplots of the relationship between tree canopy cover (%) and crop yields (tonnes/hectare), as well as the land regression fit of these models for "presumed drylands" of Angola, the United Republic of Tanzania, Mozambique, Zambia and Zimbabwe. The goodness-of-fit measure (R^2) for the regression models reveals the existence of a significant linear relation between yields and the canopy cover percentage within all countries except Mozambique.

Table 23 indicates that statistically, tree canopy cover explains between 20 percent and 50 percent of the variation in maize yields in Angola, the United Republic of Tanzania, Zambia and Zimbabwe and that a higher tree canopy cover is associated with higher yields. The fact that this broad relationship is observed across four of the five evaluated countries, reinforces confidence that the positive relationship between tree canopy cover and crop yields holds in reality and is not simply the product of 'random chance'. Note that the values for yields refer to the 2005–2015 average.

Inspecting classes of canopy cover in Figure 49, it can be shown that most tree canopy loss occurring in croplands since 2000, is within the 10–15 percent and 15–20 percent range for presumed dryland areas within Angola, the United Republic of Tanzania, Zambia and Zimbabwe. Within Zambia, a significant loss is also observed within the 45–50 percent category, i.e. in situations where the tree canopy corresponds to half the area within a given land plot.

As for current levels of cropland by tree canopy cover (the blue bars in Figure 49), it can be seen that Zimbabwe and Angola have the lowest levels, whereas in the United Republic of Tanzania and Zambia, a significant proportion of croplands have trees that cover 10 percent to 20 percent.

5.4.2 Past trends in tree canopy cover

From 2000 to 2019, there has been a 34 percent decline in tree canopy cover within the croplands of the United Republic of Tanzania.[90] Using the statistical relationship established (Table 22), this has resulted in the reduction of maize yields from an average of 1.53 kg/hectare to 1.43 kg/hectare (Table 24). If tree canopy cover continues to decline at the same pace, canopy cover by 2050 will only cover 1.5 percent of a given agricultural plot. In this situation, average crop yields will decrease to 1.27 kg/hectare.[91] This is referred to as the business-as-usual (BAU) scenario.

[89] The real interest rate is equal to the nominal lending interest rate adjusted for inflation. It is not appropriate to use the nominal rate, since most variation in these rates is due to changes in inflationary expectations, whereas the rate of return on capital (e.g. factories or equipment) is fairly stable over time.

[90] data used for this assessment were obtained from satellite imagery, which does not distinguish between a field under cultivation versus fallow land. Typically, trees regenerate during fallow periods. By lowering fallow periods overall (due to higher competition and demand for land), there will also be a lower canopy cover. Thus, the trend being observed could be attributable to shortening fallow periods, as well as diminished tree density and lack of regeneration within the croplands used.

[91] Keeping other factors constant such as climate change impacts.

Figure 48: Scatterplots of the relationship between tree canopy cover (%) and crop yields (tonnes/hectare), as well as the land regression fit of these models for "presumed drylands" of Angola, Tanzania, Mozambique, Zambia and Zimbabwe

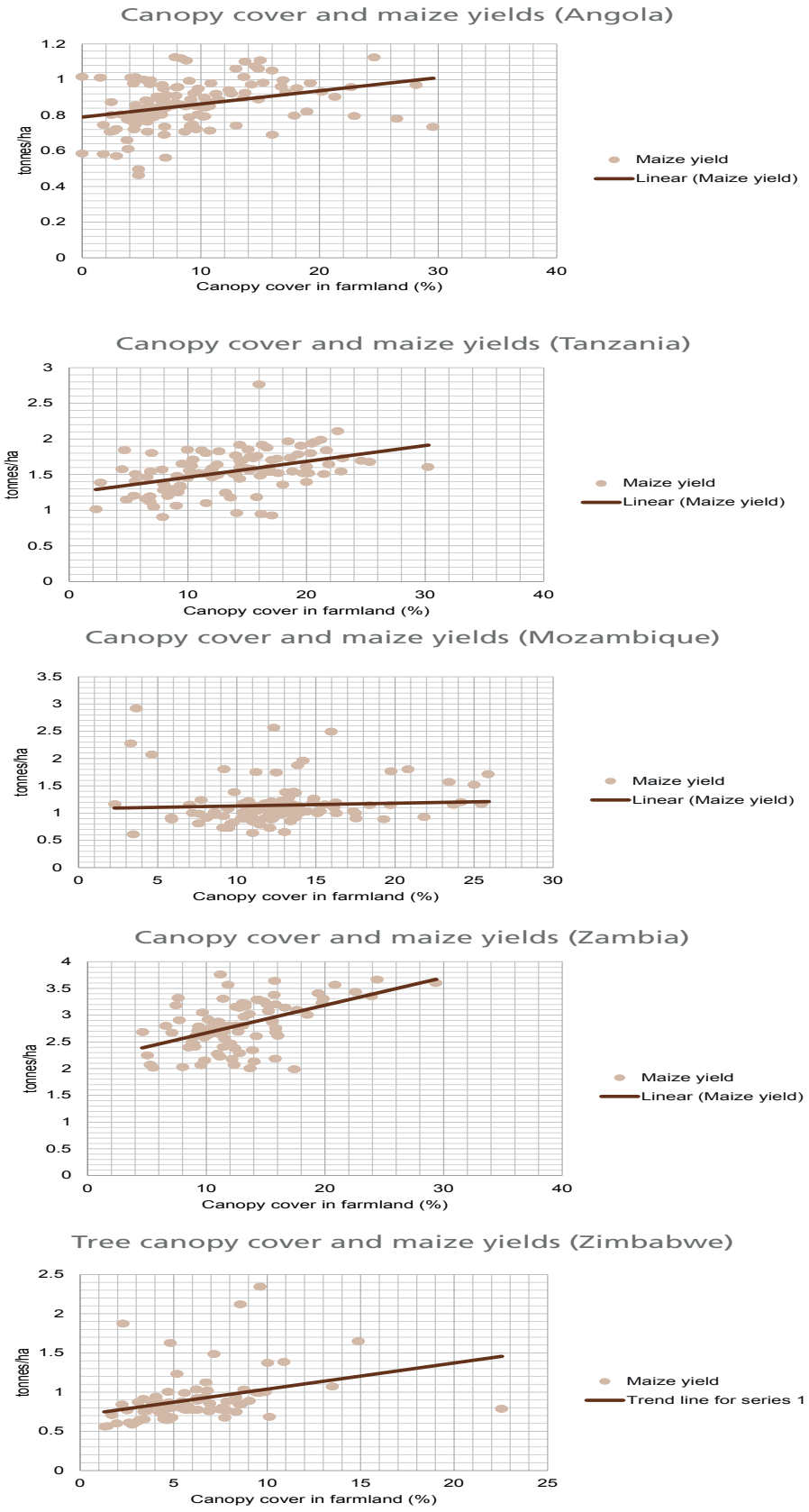


Figure 49: Tree canopy area loss within croplands from 2000–2019 (light brown) and cropland area in 2019 (dark brown) in "presumed drylands" of Angola, the United Republic of Tanzania, Mozambique, Zambia and Zimbabwe

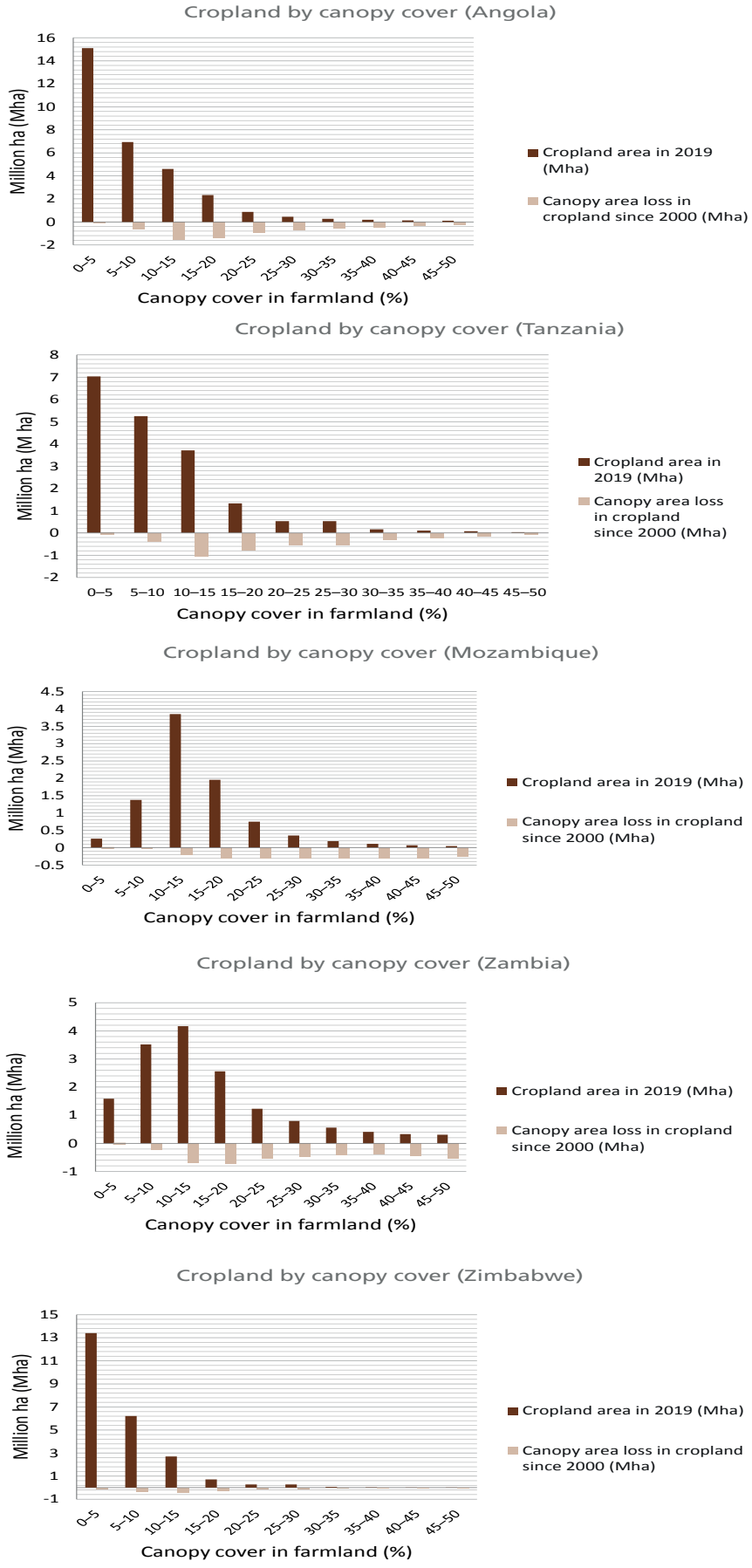


TABLE 22
Statistical relationship between tree-canopy cover and maize yields using linear regression analysis

Country	Slope	Significance	Multiple R2	N (pixels)
Angola	0.005	0.00488316	0.24	124
Tanzania	0.022	0.00000775	0.46	102
Zambia	0.052	0.00000042	0.51	88
Zimbabwe	0.033	0.00211056	0.34	81

5.4.3 The benefits of regenerating tree canopy cover within "presumed drylands" of the United Republic of Tanzania

Under the LDN1 scenario, it is assumed that efforts are made to avoid further declines in tree canopy cover, and consequently a stabilization in canopy cover is achieved relative to most recent observed measurements (from 2019). Alternatively, and in coherence with the United Republic of Tanzania's land degradation neutrality targets – notably, the improvement of land productivity in 8.5 million hectares of cropland by 2025 – efforts are being made to increase the productivity of croplands. In the LDN2 scenario, it is assumed that tree canopy cover is regenerated to 2000 levels (Table 23). The implications of these scenarios on tree canopy cover and maize yield trajectories are illustrated in Figure 50 and Figure 51.

TABLE 23
Tree canopy cover and maize yield trajectories under BAU, LDN1 and LDN2 scenarios (*Most recent observation)

Tanzania	Year 2000	Current (2019)*	BAU projection by 2050	LDN1 by 2050 (maintenance of 2019 tree canopy levels)	LDN2 by 2050 (regeneration of tree canopy cover to 2000 levels)
Tree canopy cover (%)	13.2	8.7	1.5	8.7	13.2
Yields (tonnes/ hectare)	1.53	1.43	1.27	1.43	1.53
Decline in tree canopy cover from 2000–2019 (%)	34				

Figure 50: Past tree canopy cover trend and implications of BAU and LDN scenarios on land productivity

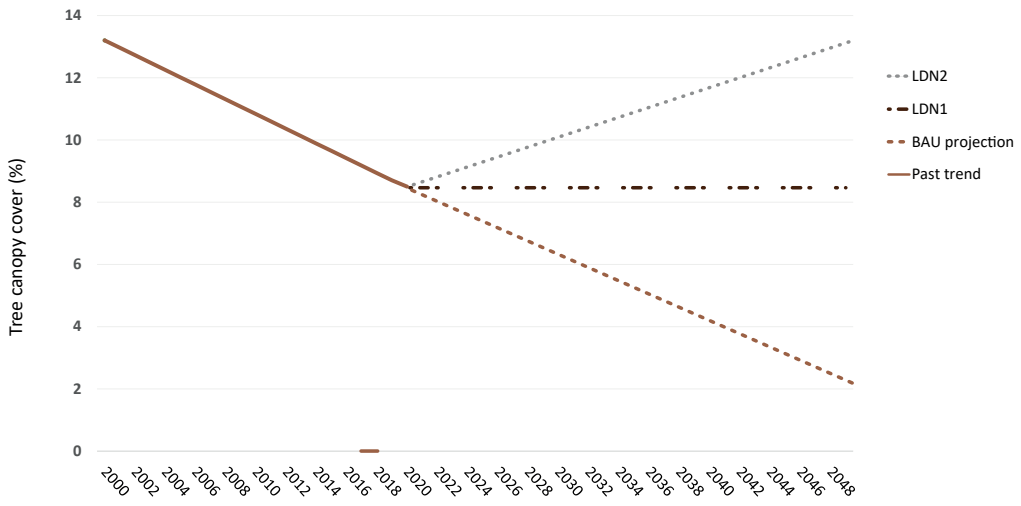
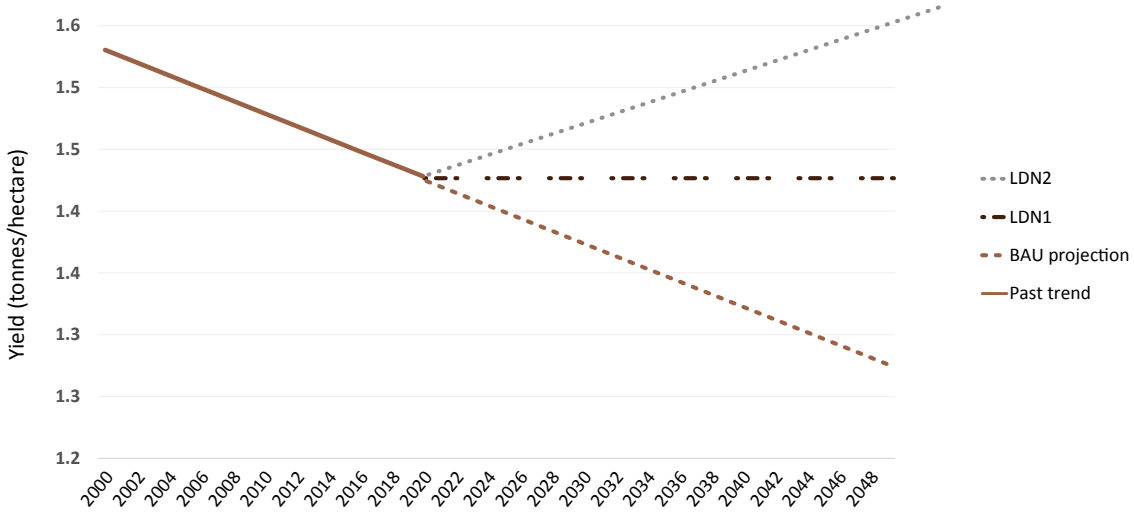


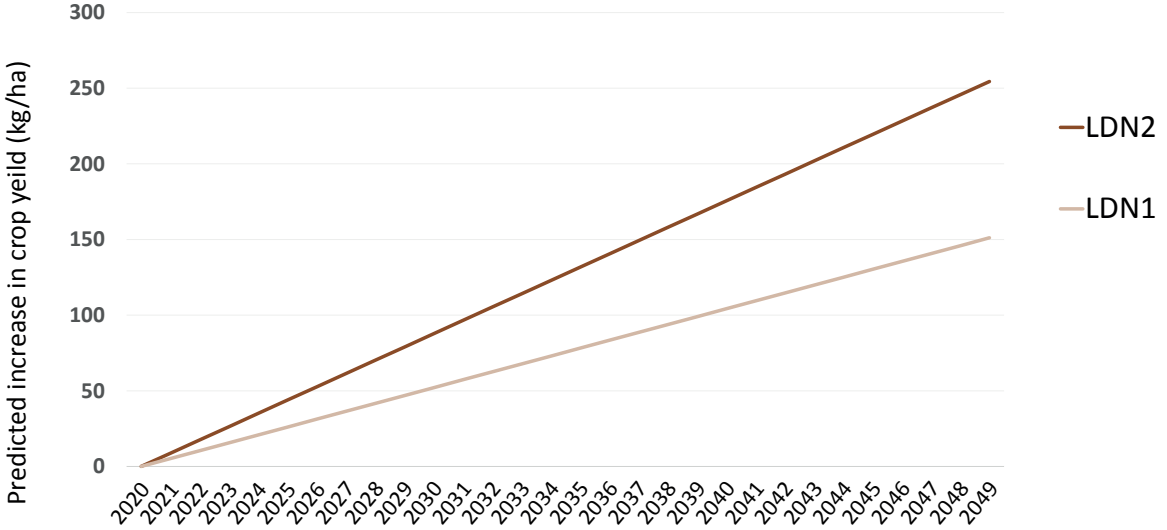
Figure51: Predicted maize yields (tonnes/hectare) in BAU and LDN scenarios based on tree canopy cover trend



5.4.4 Economic benefits of maize yield increases

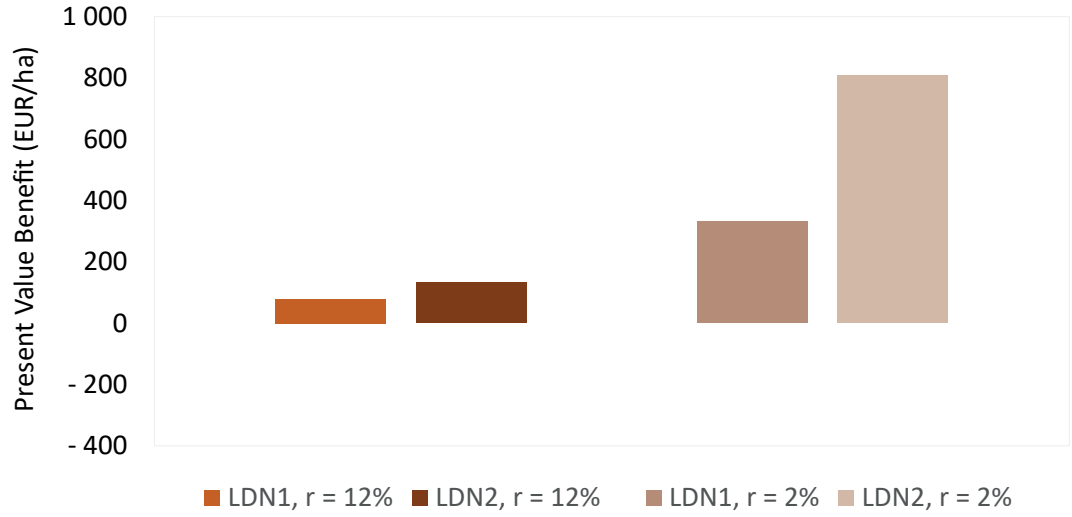
Assuming an FOB price of EUR 271/tonne (= EUR 0.138/kg), the United Republic of Tanzania can expect a societal benefit of EUR 78/hectare in present value terms, i.e. maintained cropland productivity, if tree canopy cover is stabilized at current levels, using the United Republic of Tanzania's real interest rate of 12 percent (under LDN1 scenario; Figure 52).

Figure 52: Predicted increase in maize yields (kg/ha) under LDN1 and LDN2 scenarios



If tree canopy cover can be regenerated to 2000 levels, the expected present value benefit is in the order of EUR 132/hectare from improved cropland productivity (under scenario LDN2). This corresponds to an average annual benefit of EUR 9.8 (scenario LDN1) to EUR 16.5 (scenario LDN2) per hectare. Discounting future benefits at the rate of 2 percent, the societal benefit for the 2021–2050 period is in the order of EUR 333/hectare, if tree canopy cover is stabilized, and EUR 809/hectare, if canopy is regenerated to 2000 levels (Figure 53). As such, that translates into an average annual benefit of EUR 15.2 to EUR 37.0/hectare of land regenerated (see Table 25).

Figure 53: Present value benefit of stabilizing (scenario LDN1) or regenerating (scenario LDN2) tree canopy cover relative to the BAU trajectory



5.4.5 Feasible reforestation strategies and regeneration costs

With seasonally dry forest and woodland species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*, Miombo woodlands have extensive root systems that facilitate regeneration after harvesting (Grundy, 1995). Natural regeneration occurs rapidly, usually just a few years after tree harvesting or abandonment of cropland (Williams *et al.*, 2008; Gumbo *et al.*, 2018). In this sense, farmer-managed natural regeneration (FMNR) appears a promising strategy to help increase tree densities in cropland.

Moreover, FMNR is also known as a low-cost strategy for land restoration. When farmers are familiar with FMNR and begin to adopt it, the average costs per hectare of promoting on-farm natural regeneration are lower and they can produce fruit for decades without much further investment (Cemanski, 2015; Reij and Garrity, 2016). According to Rinaudo (2020), the low cost can help understand how farmers in Niger – most of whom had no support from projects or governments – managed to regenerate 200 million trees over 20 years.

In terms of some existing estimates for the costs of implementing and managing FMNR schemes, Fungo *et al.* (2020)[92] found implementation costs to be in the order of EUR 190/hectare (for fencing and pruning in the first year) and annual maintenance costs of EUR 16.5/hectare. In Rinaudo (2020), FMNR implementation costs are estimated to be in the order of around USD 14/hectare in labour equivalent, but because FMNR continues to spread beyond the life of a project, the cost per hectare continues to decline over time.

In the Upper West Region of Ghana, FMNR implementation costs associated with an increase in tree density of 12 to 33 trees/hectare are in the order of EUR 20/hectare for new equipment in the first two years, with labour costs for pruning of EUR 16/hectare in year 1 to 3, and subsequent annual labour costs for thinning at EUR 8/hectare from year 4 (Westerberg *et al.*, 2019). Using the latter estimates, the total present value (PV) cost is in the order of EUR 159/hectare over a 29-year period (2021–2050) at an interest rate of 12 percent, and EUR 277/hectare in present value terms at an interest rate of 2 percent. The estimates by Fungo *et al.* (2020) amount to a present value cost of EUR 324/hectare (12 percent discount rate) to EUR 671/hectare (2 percent discount rate) for the 2021–2050 time period. Comparing these estimates against the present value benefits of enhanced tree canopy cover, Table 24 shows that increasing tree canopy cover, with an opportunity cost of capital of 2 percent, is economically defendable when considering the benefits from improved crop yields. Using the real interest rate of 12 percent, the benefits of enhanced crop yields do not

[92] Fungo *et al.*, 2020. Farmer-Managed Natural Regeneration (FMNR) (Uganda). WOCAT database 2017, updated 2020. https://qcat.wocat.net/en/wocat/technologies/view/permalink/2769/

outweigh the implementation and management costs. Furthermore, there are other major benefits from tree canopy cover regeneration that have not been accounted for here, as argued below.

TABLE 24
Per hectare present value costs and benefits from LDN scenarios

Scenario	LDN1	LDN2	LDN1	LDN2
Discount rate		r = 12%		r = 2%
PV benefits per hectare (2021–2050) (EUR)	78	132	333	809
Average annual benefit (EUR)		9.8 16.5	15.2	37.0
PV cost per hectare from literature (2021–2050) (EUR)		159 to 324		277 to 670

5.5 DISCUSSION AND CONCLUSIONS

The analysis above shows that the regeneration of trees within farmland (to year 2000 levels) leads to crop yield increases of up to 250 kg/hectare, providing average annual present value benefits in the order of EUR 16.5 to EUR 37.0 per hectare. Moreover, the tree canopy cover and maize yield relationships found for Zambia and Zimbabwe are even more pronounced (Table 23), relative to the United Republic of Tanzania, suggesting that the regeneration of tree canopy cover can in some cases provide higher maize yields than those estimated here.

As argued in the introduction, trees also provide crucial sources of income from timber and NTFPs, e.g. fruits, nuts, fuelwood and construction materials. Evidence suggests that the additional income from forest products from regenerated trees within FMNR systems may be even greater than the returns from enhanced crop yields (Westerberg *et al.*, 2019). Furthermore, from a whole economy perspective, the regeneration of the tree canopy cover also provides important regulating ecosystem services, such as carbon sequestration, groundwater infiltration and improved water yields, erosion control and microclimate regulation as also highlighted in the valuation study of the Cerrado. It was beyond the scope of this assessment to account for these benefits.

Using the United Republic of Tanzania's real interest rate, the net present value estimates above (Table 24) suggest that crop yield increases alone will be insufficient for inducing farmers to take up FMNR. If the value of timber and NTFPs had also been accounted for in this study, it is likely that FMNR would be considered as being profitable. In addition, given the many public goods provided by forest landscapes, there is arguably a case for deploying public funds and grants, in order to support farmers cover some of the initial investments associated with implementing FMNR. Discounting future costs and benefits at 2 percent, net present value (NPV) benefits from FMNR uptake with respect to yield increases only is positive. This approach would have to be accompanied by appropriate extension services, thus bridging forestry and agricultural 'curricula', while also raising awareness among farmers about the prospects of increasing crop productivity and income from valuable timber and non-timber products.

Consulting current integrated land management adoption rates from the Katavi and Tabora regions in the United Republic of Tanzania, it is worthwhile to note that 68 percent of households use at least one sustainable land management strategy – manuring, crop rotation, intercropping, animal urea, crop residues, fallowing and agroforestry. Nevertheless, the use of native nitrogen-fixing leguminous trees is uncommon, with only 8 percent of producers planting or regenerating trees (FAO and GEF, 2020). As such there remains high potential for upscaling tree regeneration and tree planting efforts.

For farmers to enjoy benefits from the regeneration of on-farm tree cover, however, also depends on strong land tenure. According to FAO (2020), following a SHARP[93] assessment in the Katavi and Tabora regions, uncertainty over landownership remains an important obstacle to on-farm tree growing, alongside extreme weather events and pest outbreaks. Furthermore, limitations on labour are likewise frequently acknowledged in the literature, leading to discussions on the need for 'mechanisation' that is compatible with FMNR and agroecology (Marongwe *et al.*, 2011). On

[93] http://www.fao.org/in-action/aicca/tools-and-methodologies/sharp/en/

one hand, examples include smaller tractors and cultivators, one row or hand-held planters and roller crimpers as opposed to heavy tractors on the other hand that cannot navigate between trees and require 'clean farms' (Westerberg *et al*., 2019).

In reality, however, farmers have access to working capital at high interest rates. While working capital meets seasonal needs for inputs, labour and production services, it does not allow for repayment several years later, on the basis of the returns from forest produce and enhanced crop productivity. By improving access to longer term credit lines, which allow farmers to invest in their asset base for FMNR uptake, farm enterprises can grow and move to the next level. There is also a case for reviewing existing agricultural policies that may directly and indirectly encourage deforestation and low tree densities within croplands. Indeed, the reduction of distortionary agricultural subsidies is another way of modifying the balance of private incentives for land use change that can also free up additional revenues for the implementation of sustainable land uses (World Bank, 2021).

Therefore, further research is merited to assess the full range of benefits provided by tree canopy cover regeneration and to identify tangible means for financing and encouraging the upscaling of tree planting and FMNR, while reducing incentives for deforestation and land degradation within the "presumed drylands" region of the Miombo–Mopane woodlands. As a starting point, nevertheless, this assessment is an urgent call for action, so as to halt, or even better, reverse the current pace of tree cover loss, and thus safeguard food security and land productivity within the "presumed drylands" biome of the Miombo–Mopane woodlands.

THE MIOMBO WOODLANDS

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6. Biomass, biodiversity, livelihoods and economic benefits from the adoption of different grazing management approaches in the Qinghai–Tibetan Plateau

The degradation of rangelands negatively impacts the provisioning of ecosystem services, with direct consequences for human wellbeing. In order to assess how livelihoods may be improved through the regeneration of rangelands, the available literature was investigated to better understand potentially viable sustainable rangeland management strategies in the Qinghai-Tibetan Plateau (QTP) and the economic value of adopting these. However, currently, the literature remains inconclusive. As shown below, experimental studies into maintaining or improving grassland conditions indicate varying and sometimes contradicting outcomes, in relation to implementing grazing bans, rotational grazing, adjustments to stocking rates and other sustainable land management (SLM) techniques. It is therefore not possible to recommend or assess the economic value of adopting either of these approaches, at a distance and without on-site data collection focusing on one of the case study sites in question. Nevertheless, a good starting point can be provided by summarising some key lessons from the existing literature.

With a grassland area of around 1.5 million square kilometres, the QTP plays a vital role in climate regulation and ensuring water security in Asia, while also contributing to global carbon cycling and the protection of unique species (e.g. Cai, Yang and Xu, 2015), as well as providing pastoral livelihoods for approximately the last 8 800 years (Cao *et al.*, 2019).

The main pathway though which pastoral communities can enjoy benefits from the regeneration of degraded pasture, is through enhanced availability of palatable biomass, leading to higher carrying capacities or reduced spending on supplementary feedstock at the household level. Biodiversity rich pasture may also improve livestock nutrition levels and lead to a lower incidence of illness among livestock (Myint and Westerberg, 2015).

In terms of grazing bans, the literature and experiments reveal varying outcomes. For example, in order to understand the effects of the Chinese government's 'Retire Livestock and Restore Pastures' ecological engineering programme, Wang *et al.* (2018) undertook a five-year controlled grazing experiment on the eastern side of the Qinghai–Tibet Plateau in the Gansu Province. At the end of year 5, grazing exclusion from alpine meadows showed no significant difference in standing herbage biomass, nor in species diversity, compared with either continuous grazing or rotational grazing.

Other studies also noted that grazing exclusion and bans can have negative impacts on biodiversity through reduced plant density, plant species richness and evenness in warm and cold season meadows on the QTP Plateau (Wu *et al.*, 2009, 2017; Li *et al.*, 2018). In another study in the alpine meadow-steppe of the north-eastern QTP, investigating continuous grazing versus grazing exclusion of three, six, nine and 11 years, it was found that peak biomass occurred in the 6-year exclusion plot, allowing aboveground biomass to increase by 9-fold relative to the continuously grazed setting (Li *et al.*, 2018). Moreover, after six years, the soil moisture content and soil organic carbon increased by 66 percent and 53.4 percent, respectively, relative to continuous grazing, suggesting that enclosures can also mitigate impacts on ecosystem services. As such, increases in biomass compared with observations recorded in the grazing plots are consistent with other studies (Wu *et al.*, 2009; Wang *et al.*, 2016).

However, 11 years of grazing exclusion allowed the vegetation to be dominated by a few species,

with strong colonization abilities. Hence, plant diversity decreased, with 10 species being lost in the 11-year grazing exclusion treatment compared with the 6-year grazing exclusion treatment (Li *et al*., 2018). In terms of plant community diversity and structure, Li *et al.* (2018) concluded that long-term grazing exclusion (i.e. beyond nine years) is unnecessary and therefore the optimum exclosure duration is six years for moderately degraded *Elymus nutans–Kobresia humilis* type alpine meadow-steppe on the north-eastern QTP.

Proponents of systems such as multi-paddock adaptive grazing[94] and holistic planned grazing, for example, hold that it is within the power and hands of pastoralists themselves (whether at the community- or individual household-level) to adapt herd sizes, herd movements, create forage reserves, enclosures and pasture recovery periods, so as to produce optimal levels of nutritious forage – provided adequate training is available, including manuals such as with 'hands-on' forage monitoring tools (e.g. Savory Institute, 2018).

Besides the sometimes contrasting results from the different studies, other factors may need to be taken into consideration. As such, Zhen *et al*. (2018) have shown that the Chinese government's decisions strongly influence the chosen restoration path, since in most cases "herders simply adopt government recommended approaches". In addition, in regard to these approaches and actual experience from the implementation of government programmes, Zhen *et al*. (2018) analysed the major restoration approaches – namely, enclosures, grazing bans, 'deratization', seeding with perennial grasses, forage crop cultivation and construction of warm sheds[95] – as adopted by a sample of representative households in the QTP.

Zhen *et al*. (2018) found that these grassland conservation policy initiatives had all been effective in halting grassland degradation and allowing vegetation cover to increase across all study sites. Furthermore, households that employed a combination of approaches tended to rear more animals, had higher resilience to risks and generated greater income than those households who did not. For example, herders, who harvested forage grasses in October and used it to feed their animals during the winter, were able to reduce livestock losses from natural disasters and cold spells, in comparison to those practising an enclosure only approach. Likewise, in terms of total household net annual income derived from pastoral livelihood activities, households using forage crop cultivation, warm sheds and enclosures had the highest household annual net income (CNY 90 823.7), followed by households using enclosures, deratization and grass seeding (CNY 88 846.6), while those practising grazing enclosures (CNY 57 490.7) or grazing bans only (CNY 35 736.3) fared less well in generating income.

Indeed, there is evidence that herders who have adopted grazing bans have not been compensated sufficiently to overcome the foregone income from grazing (Cao *et al*. 2019). These findings highlight the fact that ecological concerns need to be balanced with economic concerns, and suggest that under certain management initiatives, balanced ecological and economic development is possible when appropriate management approaches are adopted. However, an evaluation and monitoring of grassland conditions and farm livelihoods are required in order to readjust restoration policy and associated grazing management approaches in a timely manner (Zhen *et al*., 2018). So far, the literature has been inconclusive as to what the optimal sustainable grazing management strategies consist of and the economic value of adopting these. Further research is merited to determine and assess the full economic benefits of adopting sustainable rangeland management approaches in the QTP.

[94] http://standardsoil.com/our-approach/amp-grazing/

[95] Enclosure is a basic approach for grassland restoration with over 83.1 percent of households fencing their pasture (at least their winter pasture) with barbed wire; deratization was another important approach and adopted by about 61 percent of households, mainly in the 'black soil type' of degraded grassland because of serious rodent damage; replanting perennial grasses by reseeding has been applied in the Maduo area and in other pastures where grazing is prohibited; planting forage crops (annual herbs) and constructing warm sheds for livestock have been implemented. Herders normally used a combination of these five restoration approaches for different pastures, warm-season pastures (from June to October), cool-season pastures (from November to the following May), and unused grasslands.

7. Recommendations

While "presumed drylands" have an aridity index greater than or equal to 0.65 and cannot thus be classified as drylands (UNEP–WCMC, 2007), they nevertheless have dryland features making them vulnerable to the same challenges that drylands with aridity indices below 0.65 are facing. At the same time, they are still relatively rich in biodiversity, have higher tree cover than the strictly defined drylands and as such are crucial sources of livelihoods for numerous people, while delivering many important ecosystem services. They likewise provide diverse opportunities for investments that would help achieve land degradation neutrality.

However, "presumed drylands" are presently threatened due to both ongoing climate change and human impacts. Thus, it is of particular importance to engage in actions to prevent further degradation of these areas. To prevent such a negative trajectory, one should build on the existing, rich resource base and the practices and good examples of sustainable management in agrosilvopastoral systems.

"Presumed drylands": adopting practices to address land degradation

In the Cerrado, "presumed drylands" cover 173.9 million hectares, in the Miombo–Mopane woodlands 265.6 million hectares, and in the Qinghai–Tibetan Plateau 152.9 million hectares, which adds up to 592.4 million hectares, i.e. slightly over 55 percent of all "presumed drylands" globally. The three study areas represent a vital resource base for millions of people and they need to be maintained in a good ecological state in order to ensure future livelihoods.

The three study areas differ in regard to environmental and socioeconomic conditions and include different approaches to addressing land degradation. While the QTP is practically treeless, forest and other wooded land cover a large area of "presumed drylands" in the other two study areas, providing opportunities for utilising agrosilvopastoral systems and other sustainable land management practices to support LDN. Furthermore, tree cover is to some extent present in large parts of areas outside the forest in "presumed drylands": 57 percent of grassland and 34 percent of cropland have at least some tree cover.

The widespread issue of land degradation in the three case study areas demonstrates the need for integrated approaches that combine different tools and practices, simultaneously tackling various issues. Adopting, adapting and upscaling different practices to address land degradation and to maintain resilient systems require the consideration of complex social, economic and environmental dimensions, and should be based on integrated land use planning within a landscape approach (Haddad, Ariza and Malmer, 2021). Environmental factors are crucial and the application of agroforestry systems or SLM practices is often intricate and site specific, and thus needs to be adapted locally. In addition, introducing agroforestry or SLM practices as technical solutions based on recognition of environmental conditions is not enough. It is also necessary to invest in the active encouragement of farmers to adopt such practices. For example, Martinelli *et al.* (2019) recommended that farmers in the Cerrado be encouraged to adopt agroforestry practices by being shown the benefits these would entail. As there are different types of farmers in the Cerrado, it would be important to develop targeted messages for the different groups, e.g. large scale soy producers and small scale family farmers.

Furthermore, the literature highlights the need for well-designed policies that are adapted to local contexts and operate in good governance systems. For example, the importance of formal policies for increasing local participation in environmental management decisions was emphasised in a study of land use changes in the Cerrado (Garcia and Ballester, 2016). In many cases, such as fire policies in the Cerrado, literature suggests that existing policies are changed. Likewise, for the Miombo–Mopane woodlands, the need for ensuring food security and poverty alleviation and dealing with tenure and gender issues when addressing land degradation has been shown

(Kwesiga *et al.*, 2003). However, researchers also stress that considerable scaling up of agroforestry is required if these issues are to be addressed (Kwesiga *et al.*, 2003; Kakhobwe *et al.*, 2016), and therefore improved policies can help facilitate the scale of the changes needed.

For the Qinghai–Tibetan Plateau, approaches should be sought that combine modern stockbreeding technologies with the best aspects of nomadic pastoralism, for which Governmental support is required, particularly in encouraging livelihood diversification if needed in some locations (Yan, Wu and Zhang, 2011), and that cultural aspects of the pastoral systems are considered in restoration and rehabilitation efforts (Fayiah *et al.*, 2020).

Human pressure on presumed dryland resources as in other dryland zones is still increasing and accentuated due to a mix of factors, such as climate change, agricultural expansion, increased water stress and high population growth. Adopting the guidance for transformative projects and programmes,[96] developed by UNCCD and the Global Mechanism to help countries achieve LDN targets, have proven effective options in setting measurable targets for land management in terms of health and productivity, while achieving many of the Sustainable Development Goals (SDGs).

The data and information provided in this report can be used to support countries prioritise their investments in restoring and avoiding further degradation in "presumed drylands", and thus to attain significant societal and environmental benefits. In particular, the trade-offs and synergies of different investment options can be assessed for the "presumed drylands" to enable more informed decision-making processes. For example, the assessment is able to estimate the value of production losses associated with changing microclimates due to land degradation in "presumed drylands" of the Cerrado.

Based on the economic analysis presented in this assessment, key policy recommendations and associated observations are summarised per study area:

7.1 THE CERRADO : RECOMMENDATIONS AND OBSERVATIONS

- **Land degradation neutrality in "presumed drylands" of the Cerrado should be pursued as strong evidence shows it would lead to significant societal benefits.** Climate-related damage costs are in the order of USD 133 billion for the 2021–2050 timeframe, and the cost in terms of reduced agricultural productivity from reduced precipitation is in the order of USD 105 billion. Therefore, continued clearing of native Cerrado vegetation for crop production involves significant losses to society. If other ecosystem services impacted by the continued clearing of native Cerrado vegetation – such as biodiversity, recreational opportunities (and ecotourism), water yield, erosion control, wild forest products and food crop production – were accounted for, the benefits would be even more pronounced.
- **Other market-based and fiscal instruments should be explored that can reward farmers for environmental stewardship**. Cropland is likely to continue to expand in the Cerrado. Native Cerrado land is cheaper than degraded pastureland and cropland, and average annual profits are in the order of USD 495/hectare of soy cultivated. Even with reduced productivity, farmers can expect high profits, due to persistently high prices and demand for soy. Moreover, the analysis carried out here suggests that current forest carbon prices are not of sufficient amplitude to compensate for foregone profits from soy cropping. Therefore, it is relevant, for example, to extend the use of existing official low-interest credit lines for low carbon agriculture (TNC, 2019) and pursue complementary incentive-based mechanisms for conservation.
- **Distortionary agricultural subsidies should be reduced**. The recent report by the Climate Investment Funds and the World Bank[97] (2021) highlighted that environmental effectiveness can be improved by allowing tax rates to vary according to the sustainability of commodities produced, while ensuring enforcement using choke points such as ports from where products are shipped. Together with the reduction of distortionary agricultural subsidies, it is possible to modify the balance of private incentives towards cropping over degraded pastureland only, and to free up additional public revenues for implementing sustainable land use management practices.

[96] LDN Transformative Projects and Programmes | UNCCD

[97] https://www.climateinvestmentfunds.org/knowledge-exchange/transformational-change-climate-finance-insights-world-bank-and-giz

- **Regulatory measures should be addressed**. For example, while Brazil's Forest Code requires the conservation of 80 percent native vegetation on private lands in the Amazon biome, only 20 percent is required in the Cerrado (35 percent for the portion of the Cerrado is located in the Legal Amazon). Moreover, the enforcement of the Forest Code has been poor in recent years (Rochedo *et al*., 2018).
- **Use tighter legislation, market-based and fiscal instruments to influence the private sector**. There are deepening concerns over the loss of species habitat and biodiversity, and heightened awareness about the long-term ecosystem and financial risks associated with deforestation. Consumers, NGOs and investors are therefore urging food companies and financial institutions to devote more resources to addressing deforestation in their supply chains (Clancy, 2021). Unfortunately, among the companies that have made commitments to end deforestation, many have failed to deliver or to set deadlines (Taylor and Streck, 2018; Lambin *et al.,* 2018). Tighter legislation, market-based and fiscal instruments, as well as continued consumer pressure, will be necessary to tilt the balance in favour of halting deforestation and restoring degraded pastureland within "presumed drylands" of the Cerrado. The feasibility of expanding cropland over pastureland in the LDN scenarios also hinges on the possibility of implementing intensified and sustainable land management practices (such as agrosilvopastoral systems) on the remaining pastureland, in order not to compromise livestock production in the long term. To promote sustainable land management, the sector will require not only sound public policies, but also public finance both for direct investment and to enable and support private investments. Blended finance[98] can be an important part of the toolbox that governments have at their disposal to advance investments in sustainable pasture management.
- **Importantly, further research is needed to assess the additional costs associated with expanding soy production onto degraded pastureland (as opposed to onto native Cerrado vegetation).** A greater understanding of the economics of implementing agrosilvopastoral systems as a restoration option is required, as well as the full range of ecosystem service benefits (biodiversity, groundwater infiltration, wild forest produce, among others) that would be impacted by the pursuit of land degradation neutrality within "presumed drylands" of the Cerrado.

7.2 MIOMBO–MOPANE WOODLANDS: RECOMMENDATIONS AND OBSERVATIONS

- **Increasing tree densities within cropland should be viewed as an essential component of healthy and productive farmlands in the "presumed drylands" biome of the Miombo–Mopane woodlands**. Taking the United Republic of Tanzania as an example, it can be demonstrated that the regeneration of tree canopy cover to year 2000 levels would increase maize yields by an average of 250 kg/hectare, while a stabilisation of canopy cover would increase yields by 150 kg/hectare relative to the business-as-usual (BAU) trajectory. The present value benefits are in the order of EUR 159 to EUR 324 per hectare at the real interest rate of 12 percent. While maize and rice are among the most important staples cultivated in the target landscape in the United Republic of Tanzania, their production systems have low productivity and are susceptible to climate change and pests. The heavy reliance of farmers on maize and rice contributes to their increasing vulnerability to shocks (FAO and GEF, 2020[99]). It is, therefore, all the more urgent to increase farmers' access to timber, NTFPs and other sources of nutrition, including from many native trees such as fig species, the baobab, *Uapaca* spp. and *Sclerocarya birrea*

- **Getting the price incentives right is required.** Despite the existence of relevant policies to support regreening – such as the National Forest Policy (1998), the Tanzania Beekeeping Policy (1998) and the National Agricultural Policy[100] (2013) – there are a number of obstacles impeding their implementation. These obstacles include weak legal frameworks for forest management, overlapping mandates between institutions responsible for forest

[98] https://www.oecd.org/dac/financing-sustainable-development/blended-finance-principles/
[99] https://www.thegef.org/sites/default/files/webdocuments/10206_IP_SFM_Drylands_Annex_ChildProjects.pdf
[100] https://www.climate-laws.org/geographies/tanzania/policies/national-agriculture-policy-2013

management, as well as insufficient and inadequate financing instruments (FAO and GEF, 2020). Moreover, existing agricultural programmes tend to focus on supporting farming through 'conventional means' such as subsidizing inorganic fertilizers and pesticides in major maize producing regions in Tanzania (USDA Foreign Agricultural Service, 2019).[101] In this regard, there is a case for "getting the price incentives right," which is mostly the role of tax and subsidy policies. In general, taxes and other fiscal instruments are an underutilised but key component of climate-related land use policy interventions (IPCC, 2019). To the extent that agroforestry and farmer-managed natural regeneration (FMNR) provide many public services (carbon sequestration, microclimate regulation, erosion control, groundwater infiltration, biodiversity, among others), there is a solid case for supporting farmers' efforts to regenerate the tree canopy cover.

- **Catalytical capital[102] from public sources can be used to mobilise private sector investment through blended finance mechanisms.** Longer credit lines and lower interest rates are key to allowing farmers to invest in FMNR and agroforestry, as the returns may not be immediate, especially when it comes to the harvesting of forest produce.
- **Ensuring that FMNR is cheaper and easier for farmers to invest in the regeneration of tree canopy cover.** Labour limitations are also frequently acknowledged as a barrier to regreening, leading to calls for 'mechanisation' that is compatible with FMNR and agroforestry (Haddad, Ariza and Malmer, 2021; Marongwe *et al*., 2011). With a lack of tenure security, representing an additional barrier, policies and initiatives should be aimed at making it cheaper and easier for farmers to invest in the regeneration of tree canopy cover.

This assessment should be a catalyst for further on-the-ground research to inform cost-effective investments that balance environmental, social and economic dimensions.

[101] https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Grain%20and%20Feed%20Annual_Dar%20es%20Salaam_Tanzania%20-%20United%20Republic%20of_4-9-2019.pdf

[102] Catalytic capital is investment **capital** that is patient, risk-tolerant, concessionary, and flexible in ways that differ from conventional investment. It is an essential tool to bridge **capital** gaps and achieve breadth and depth of impact, while complementing conventional investing.

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9. Annexes

Annex 1: Different land use categories adopted in the global assessment

Land use categories of the Global Forest Resources Assessment 2015 (FAO, 2012a)

- Forest

Land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use.

- Other wooded land

Land not defined as "Forest", spanning more than 0.5 hectares, with trees higher than 5 metres and a canopy cover of 5–10 percent, or trees able to reach these thresholds, or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use.

- Other land

All land that is not classified as forest or other wooded land

- Explanatory notes
- Includes all land that is predominantly under agricultural or urban land use and has patches of tree cover spanning more than 0.5 hectares, and a canopy cover greater than 10 percent of trees able to reach a height of 5 metres at maturity. It includes both forest and non-forest tree species. This is classified as "Other land with tree cover".
- Inland water bodies

Inland water bodies generally include major rivers, lakes and reservoirs.

Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance

- Forest land

This category includes all land with woody vegetation consistent with thresholds used to define forest land in the National Greenhouse Gas Inventories. It also includes systems with a vegetation structure that currently fall below, but *in situ* could potentially reach the threshold values used by a country to define the forest land category.

- Cropland

This category includes cropland, including rice fields and agroforestry systems where the vegetation structure falls below the thresholds used for the forest land category.

- Grassland

This category includes rangelands and pasture that are not considered cropland. It also includes systems with woody vegetation and other non-grass vegetation such as herbs and bushes that fall below the threshold values used in the forest land category. Furthermore, the category includes all grassland from wild lands to recreational areas, as well as agricultural and silvopastoral systems, consistent with national definitions.

- Wetland

This category includes areas of peat extraction and land that is covered or saturated by water for all or part of the year and that does not fall into forest land, cropland, grassland or settlements categories. It includes reservoirs as a managed subdivision and natural rivers and lakes as unmanaged subdivisions.

- Settlements

  This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with national definitions.

- Other land

  This category includes bare soil, rock, ice and all land areas that do not fall into any other of the five categories.

Annex 2: Global data collection and analysis.

DATA COLLECTION AND ANALYSIS

The design of the Global Drylands Assessment benefited from consultation with drylands experts engaged in the Action Against Desertification (AAD) initiative and the Rome Promise collaborative network.[103] The survey was set up using Open Foris Collect software and then embedded in Open Foris Collect Earth.[104] For each sample plot, data on 77 variables describing the sample site were collected through the visual interpretation of available satellite images. The characteristics were selected to describe land cover, land use, land-use change and other significant land dynamics (such as desertification and greening), along with biophysical indicators over the reference period (2000–2015). The starting year, 2000, was selected because it is the first year for which consistent global coverage of satellite data (Landsat 7) is available.

Different classification schemes were used, depending on the variable. For example, land use was classified based on both the four categories of the Global Forest Resources Assessment (FRA) 2015 (forest, other wooded land, other land, inland water bodies) (FAO, 2015b) and the six land-use categories of the Intergovernmental Panel on Climate Change (IPCC) (forest, cropland, grassland, wetlands, settlements, other land) (IPCC, 2006) (see Annex 1).

The assessment adopted the definition of forest used in FRA 2015: "Land spanning more than 0.5 ha with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use" (FAO, 2012a).

Other wooded land is "land not defined as 'forest', spanning more than 0.5 ha, with trees higher than 5 metres and a canopy cover of 5–10 percent, or trees able to reach these thresholds; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use" (FAO, 2012a).

The data collection form in Collect Earth was structured to guide operators in the survey process, starting with the identification and quantification of simple land elements (e.g. trees and shrubs) and the identification of the main land-use category. The approach enabled operators to report on impacts and disturbances over the reference period whenever these could be detected within plots. Collect Earth projected each sample plot as a rectangle containing a grid of 49 control points, enabling users to assess the proportion of plots taken up by trees, shrubs and other land elements.

Only one land use could be assigned per sample plot. In the case of FRA categories, the assigned land use was that which covered the greatest area. For example, a sample plot with more than 10 percent tree cover was not classified as forest unless forest was the prevailing land use within the area of the whole plot. Land with trees not constituting forest includes settlements and croplands (e.g. the land use might be agroforestry). In the case of IPCC categories, a hierarchical rule was applied to define the main land use, as explained in Martínez and Mollicone (2012).

Subtypes of vegetation were also identified as subclasses of IPCC categories (see Annex 1). However, only the higher-level classifications are presented in this report, as the interpretation of subtypes can be less reliable.

In the visual interpretation, each expert used his or her knowledge of the landscape characteristics of the sampling location, as well as information provided by remote-sensing data to support the assessment. For example, crops were classified as irrigated based on the visible presence of pivots, pipes, water tanks or nearby rivers, or as perennial crops based on the visibility of crops such as bananas or coconuts in

[103] http://www.fao.org/3/bo604e/bo604e.pdf
[104] http://www.openforis.org/tools/collect-earth/

the very-high-resolution imagery.

The simultaneous use of low-resolution and very high-resolution satellite imagery facilitated the assessment of land use and detection of land-use change. For assessment of some land elements (e.g. distinguishing between trees and shrubs), satellite data and local knowledge were sometimes insufficient, however, and a decision rule based on the crown diameter of trees and shrubs was therefore adopted. Elements with a crown diameter larger than 3 m were considered trees; elements with smaller diameters were considered shrubs. The Collect Earth tool does not allow tree height to be assessed; shadows were used in addition to the crown-diameter threshold to determine whether elements were sufficiently tall (i.e. 5 m or taller, consistent with the definition of forest used in the assessment) to be considered trees.

The FRA definition of forest includes areas with young trees that have not yet reached but are expected to reach a canopy cover of at least 10 percent and tree height of 5 m or more. It also includes areas that are temporarily unstocked as a result of clear-cutting as part of forest management practice or natural disasters, and that are expected to be regenerated within five years. Consequently, some areas classified as forest in the assessment may be identified as having zero canopy cover.

SAMPLING DESIGN

The assessment draws on information from 213 782 sample plots located across the world's drylands. Each plot measured 70 × 70 m (approximately 0.5 ha), a size corresponding to the smallest patch that qualifies as forest according to the forest definition used in the assessment.

A stratified systematic grid of sample plots across the drylands was applied. Each aridity zone was treated as an independent stratum. The dry subhumid zone was sampled at a higher intensity than the hyperarid zone because the probability of finding trees is lower in areas with higher aridity. The relative sampling intensity assigned to each aridity zone was as follows: hyperarid = 0.5; arid = 1; semi-arid and dry subhumid = 1.5

The error in the estimation of forest area has two main sources: sampling error and measurement error. The sampling error for the estimate of forest land at the global level is about ±1 percent. The measurement error, calculated by comparing the remote-sensing data from Collect Earth with field data for a subsample of 441 plots, was estimated to be about ±8.3 percent (Bastin *et al.*, 2017).

DATA SOURCES

Sample plot data were collected from online digital repositories of satellite images using Collect Earth. Typically, each plot was shown in several images representing different points in time in the period 2000–2015, although the same points in time were not available for all plots. All plots were covered by Landsat imagery (30 m-resolution), and 89 percent of plots were also described in higher-resolution images. More than half were described in images from Digital Globe[105] with a resolution finer than 1 m. The proportion of satellite image types was similar for all land-use types. The temporal profiles of intra- and interannual vegetation indices were derived from low-resolution satellite data (with ground resolution of 30 to 250 m).

IMPLEMENTATION APPROACH

The assessment was conducted through a series of regionally-focused training and data collection workshops, organized in collaboration with participants from universities, research institutes, governments and NGOs worldwide, and most of them local experts.

In the first week of each workshop, participants were instructed and trained by FAO staff. In the second week, participants collected data by assessing sample plots using Collect Earth. The purpose of this approach was to ensure that the interpretation was performed consistently in all regions and benefited from the regional and local knowledge of participants.

The regional groupings used to structure the analysis and to present the results are based on the geoscheme of the United Nations Statistics Division (UN, 2019). Of these regions, the only one for which the report does not include a chapter is Southeastern Asia, owing to the very few plots classified as drylands in this region (377 plots or 13 million hectares). Southeastern Asia falls entirely within the tropical and subtropical climatic zones and for the most part receives considerable annual precipitation. Indeed, the 377 plots assessed as drylands were all classified in the least arid zone, the dry subhumid zone.

[105] https://discover.digitalglobe.com/

DATA PROCESSING

The sample plots were divided into geographically-defined subsets, one for each regional training and data collection workshop. Assessment data interpreted by an expert for each sample plot were saved directly into a database. FAO collated all the databases into a single database and cleansed the data using automatic and visual checks. The results were generated with Saiku Analytics, a web-based software that enables users to visualise and aggregate data through a simple drag-and-drop interface. Uncertainty analysis was performed in Microsoft Excel.

Note that throughout this report and the Global Drylands Assessment report, percentages may not add up to 100 percent because of rounding up.

Annex 3: Economic valuation – Cerrado supporting materials

A: Data sources used for the integrated land-cover, climate and crop yield model

Data	Comments	Reference
Climate	Monthly maximum temperature and total precipitation, 1948–2015, 4 km resolution	Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A. & Hegewisch, K.C. 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Scientific Data, 5(1): 1–12.
	Drought frequency for Cerrado under RCP106 4.5.	Rodrigues, J.A., Viola, M.R., Alvarenga, L.A., de Mello, C.R., Chou, S.C., de Oliveira, V.A., Uddameri, V. & Morais, M.A. 2020. Climate change impacts under representative concentration pathway scenarios on streamflow and droughts of basins in the Brazilian Cerrado biome. International Journal of Climatology, 40(5): 2511–2526.
	Temperature for Cerrado under RCP 4.5.	Camilo, J.A., Andrade, C.L.T., Amaral, T.A., Tigges, C.H.P., Melo, M.L.A., Chou, S.C. & y Garcia, A.G. 2018. Impact of climate change on maize grown in the Brazilian Cerrado. Paper presented at ASABE 2018 Annual International Meeting, Detroit, United States. https://doi.org/10.13031/aim.201800967
Yields	Time series of major crop yields 1981–2016, 50 km resolution	Iizumi, T. & Sakai, T. 2020. The global dataset of historical yields for major crops 1981–2016. Scientific Data, 7(1), https://doi.org/10.1038/s41597-020-0433-7
Land cover	Biome-cover maps for the Cerrado, 1985–2019, 30 m resolution	Souza, C.M., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A, Rudorff, B.F., Hasenack, H. *et al.*, 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. Remote Sensing, 12(17): 2735.
Precipitation change due to land interactions	Historical observations of vegetation and precipitation changes in the Cerrado.	Campos, J.D.O. 2018. Variabilidade da precipitação no Cerrado e sua correlação com a mudança no uso da terra.
	Amount of precipitation in South America originating from land evapotranspiration.	Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J., Van der Ent, R.J., Donges, J.F., Heinke, J., Sampaio, G. & Rammig, A. 2014. On the importance of cascading moisture recycling in South America. Atmospheric Chemistry and Physics, 14(23): 13337–13359.

B: Accounting for increased frequency of droughts in future climate change projections

The predicted increase in drought frequency in Ukkola *et al.* (2020) is partly due to changes in global GHG concentrations and partly due to land-use changes assumed in the climate models. There is no easy way to differentiate these without undergoing extensive model runs with different assumed land-cover scenarios (Kumar *et al.*, 2013).

However, according to Zemp *et al.* (2014), about 30 percent of the precipitation in South America originates from within the continent via processes of moisture recycling from vegetation. In order to avoid double counting of the GHG and land-cover change effects in droughts, these 30 percent (=167 mm of precipitation per year) have been removed from the past time series for September to December, so as to obtain only the amount of precipitation that is driven by global circulation in the Cerrado.

The new time series of past precipitation was then taken that reflects only precipitation from global circulation patterns (original time series minus 167 mm) and the number of years calculated when precipitation was below the 15th percentile. For the historical period – between 2000 and 2019 – precipitation levels from September to December were below the 15th percentile a total of 3 years.

[106] https://en.wikipedia.org/wiki/Representative_Concentration_Pathway

With climate kept constant, it would be expected to have 4.5 drought years between 2020 and 2050. However, under climate change (RCP 4.5) the likelihood of droughts occuring is almost doubled (× 1.8) by 2040 which leads to 8.1 drought years between 2020 and 2050.

As it is not known when these drought years will take place, the drought years are randomly sampled 1 000 times for each year between 2020 and 2050 and the resulting precipitation is be around for each year. Finally, the 167 mm previously subtracted is added back for each year in order to simulate the effect of keeping land cover unchanged. For temperature, the trend in Camilo *et al*. (2018) is superimposed of an average 2.1 °C increase in maximum temperatures between 2007 and 2040 as found for the Cerrado region under RCP 4.5.

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